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Station

An Automated System for Hopper Dredge Monitoring

by Jeffrey D. Jorgeson, Stephen H. Scott

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Prepared for U.S. Army Engineer District, Norfolk

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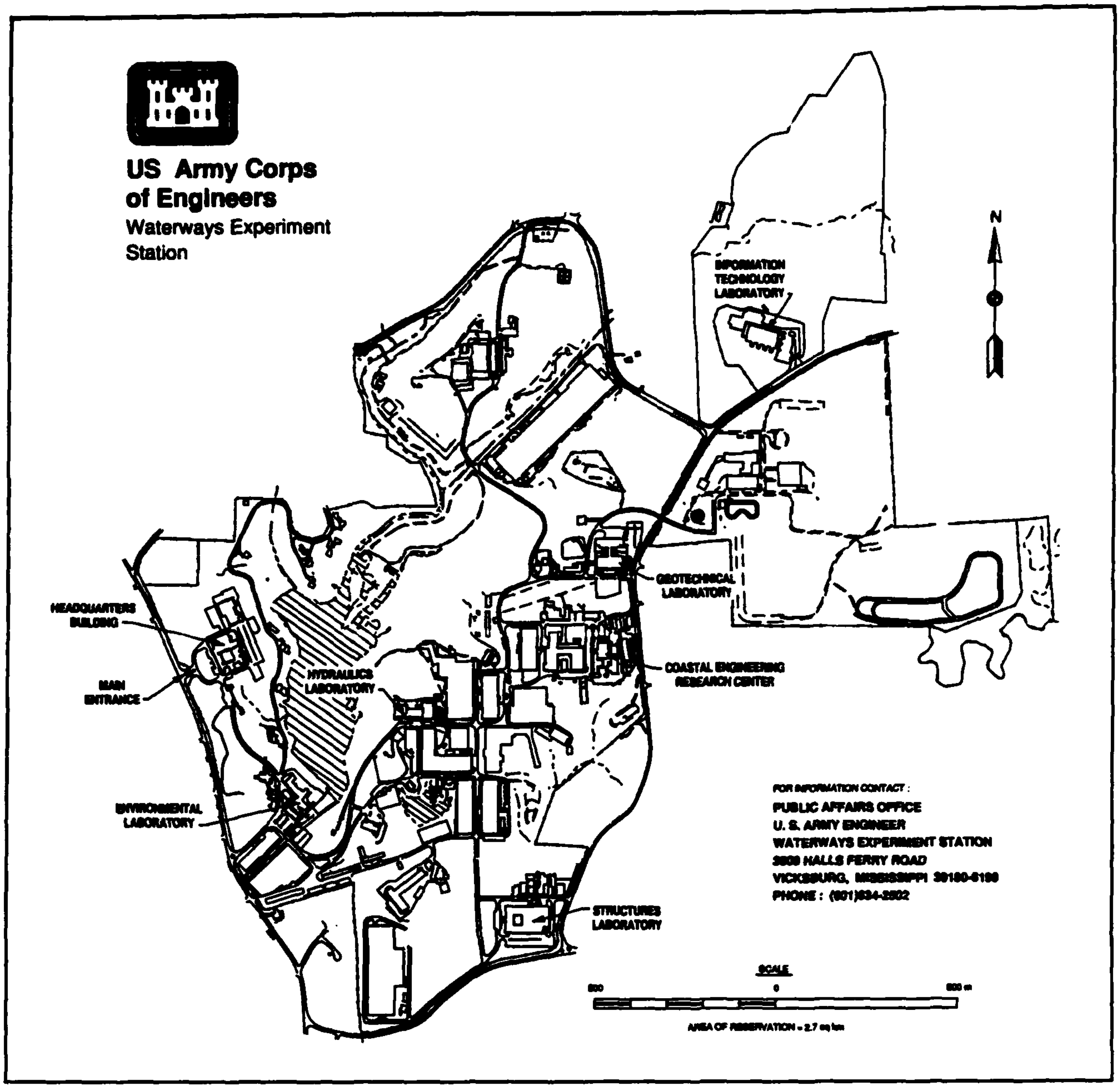

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Preface

This study was conducted by the Hydraulics Laboratory (HL) of the U.S. Army Engineer Waterways Experiment Station (WES) during the period of January 1993 to October 1993. This study was sponsored by the U.S. Army Engineer District, Norfolk.

This report was prepared by Messrs. Jeffrey D. Jorgeson and Stephen H. Scott, Estuaries Division (ED), HL. The work was performed by Messrs. Jorgeson, Scott, and Monroe B. Savage and Dr. Cary B. Cox of the Instrumentation Services Division, WES. The report was prepared under the direct supervision of Mr. William D. Martin, Chief, Estuarine Engineering Branch, ED, and under the general supervision of Messrs. William H. McAnally, Chief, ED; Richard A. Sager, Assistant Director, HL; and Frank A. Herrmann, Director, HL.

Messrs. Sam McGee and Richard Klein of the Norfolk District were Engineering Managers, Thomas Friberg of the Norfolk District was Contract Administrator, and Mr. Bill Jones of the Norfolk District served as the Quality Assurance Representative for the dredging projects involved in this study.

Special appreciation and acknowledgement is extended to the Great Lakes Dredge and Dock Company, the North American Trailing Company (NATCO), and the crew of the NATCO dredge *Northerly Island* for their support, assistance, and cooperation in the performance of this study.

At the time of publication of this report, the Director of WES was Dr. Robert W. Whalin and the Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic yards	0.7645536	cubic meters
feet	0.3048	meters
horsepower (550 foot-pounds (force) per second)	745.6999	watts
inches	25.4	millimeters
miles (U.S. statute)	1.609347	kilometers
pounds (force) per cubic foot	157.08774	newtons per cubic meter
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.4535924	kilograms
square feet	0.09290304	square meters
square inches per square foot	69.444474	square centimeters per square meter
tons (2,000 pounds, mass)	907.1847	kilograms

1 Introduction

Background

Although payment under the majority of dredging contracts is based on cubic yards dredged as determined by pre- and postdredging surveys, there are circumstances such as rapid shoaling or changing weather conditions that make payment based upon such surveys impractical. Such conditions are common when dredging a coastal inlet. In such situations it is often preferable to award a contract whereby payment to the contractor is based upon measurement of the volume of in-place dredged material in the hopper as determined by vessel displacement, commonly referred to as "bin measure." Such a contract is awarded annually by the U.S. Army Engineer District, Norfolk, for maintenance dredging of Chincoteague Inlet, Virginia.

Under a bin measure contract, the Government typically relies on records provided by the contractor to determine the volume of material dredged in each load, and thus the amount of payment due. While a Government quality assurance representative, or inspector, is assigned to the project, he/she is not present on the dredge at all times and cannot monitor every load and verify the accuracy of all of the contractor's records. Additionally, when disputes arise, the Government generally has very little information on which to judge the merit of the contractor's claim, with the exception of the records and information provided by the contractor. Therefore, a system is needed that can automatically and fairly determine the volume of dredged material in the hopper for payment under bin measure contracts and can provide a record of the dredging operation in the event of disputes. Such a system would record the necessary data for making bin measure calculations and provide a complete and unbiased record of the entire dredging project for use by both the Government and the contractor.

Determining the volume of in-place dredged material in the hopper during each load requires knowledge of the volume of material in the hopper at the start of each load, the volume of material added to the hopper during the loading process, and the weight of the material added to the hopper during the loading phase. Existing instrumentation on most dredges provides a continuous record of the total displacement of the vessel from which the weight of dredged material added to the hopper can be determined by subtracting the

total weight of the vessel at the start of a load from the total weight of the vessel at the end of that load. Electronically monitoring and recording the displacement of the dredge using pressure sensors to measure the draft was successfully done under a previous study for the Norfolk District.[1] Additionally, under the Corps of Engineers' Dredging Research Program (DRP), acoustic sensors have been successfully installed on the Corps of Engineers dredge *Wheeler* to continuously monitor the volume of material in the hopper (Scott 1992a). Thus, the technology to automatically monitor and record the necessary information for determining bin measure loads exists.

Another aspect of the dredging process that can be difficult to monitor or analyze is the effectiveness of overflowing to increase the amount of solids in the hopper. When coarse-grained sediments are being dredged, overflow is typically effective; but in fine-grained sediments, the amount of additional solids retained in the hopper during overflow is questionable. Where restrictions on the duration of overflow exist, monitoring strict compliance with that restriction 24 hours a day can be difficult. Where restrictions on the amount of overflow are being considered, some estimate of the amount of sediment that is actually retained in the hopper versus the amount that flows overboard is very beneficial. Thus, a monitoring system enabling both the duration and the effectiveness of overflow to be determined would make the monitoring, enforcement, and implementation of overflow restrictions much more feasible.

Objective

The two primary objectives of this study were to demonstrate an automated monitoring system for (a) determining the bin measure production of a contract dredge during the maintenance dredging of sandy material at Chincoteague Inlet, Virginia, and (b) monitoring a contract dredge for the amount of material retained in the hopper during the overflow process of a dredging cycle while it performed maintenance dredging of fine-grained material in the Norfolk Harbor Channel, Virginia. This report describes the integration of the displacement and hopper volume measurements into a computer-based data logging system for monitoring the dredge.

Approach

To meet these objectives, a monitoring system that would automatically measure and record the volume of material in the hopper, the displacement of the dredge, and the production meter data on a continuous basis was designed, installed, and field tested. The volume of material in the hopper was

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[1] Jeffrey D. Jorgeson, 25 June 1992, Memorandum for Commander, U.S. Army Engineer District, Norfolk, Subject: Calibration of the Hopper Load Monitoring System on the Contract Dredge ATCHAFALAYA.

determined through the use of acoustic sensors installed above the hopper, and dredge displacement was determined from fore and aft draft measurements. An additional component of the system also monitored and recorded the dredge's production meters, which measure the density and velocity of material passing through the dredge pipes. The production meter data were used in conjunction with the vessel displacement and hopper volume data to estimate the total amount of material dredged and the amount of material that was retained in the hopper during the overflow process for each load.

Two separate dredging projects were monitored for this study. The first of those was at Chincoteague Inlet, Virginia, where the hopper volume and dredge displacement data were used to determine the bin measure production for each load. The second project was in the Norfolk Harbor Channel, where the hopper volume, dredge displacement, and production meter data were incorporated into an analysis of the amount of solids retained in the hopper during the overflow process. Each of these projects, the data collected, and the results obtained are discussed in the following sections of this report.

2 The Monitoring System

The Bin Measure Concept

The concept of determining dredge production using the bin measure method involves indirectly measuring the average density of material in the dredge hopper for each load. Measuring the displacement, or weight, of the vessel and volume of material in the hopper at the beginning and end of the loading process determines the weight of material in the hopper and the volume of that material. Those values are then used to find the average density of the material in the hopper. If the in-place density of the sediment is known, then the in-place volume can be calculated for each load. The following equations show how production calculations are made once the hopper volume, vessel displacement, in-place sediment density, and water density in the dredging area are measured.

a. Bin water weight BW, lb

$$BW = V_S * \rho_w * 27\ ft^3/yd^3 \tag{1}$$

b. Total weight in hopper TW, lb

$$TW = [(D_E - D_S) * 2{,}000\ lb/ton] + BW \tag{2}$$

c. Average density in hopper ρ_H, lb/ft^3

$$\rho_H\ (lb/ft^3) = TW\ /\ (V_E * 27\ ft^3/yd^3) \tag{3}$$

d. In-place production P_i, yd^3

$$P_i = [(\rho_H - \rho_w)\ /\ (\rho_i - \rho_w)] * V_E \tag{4}$$

where

V_S = volume in hopper at start of load cycle, yd^3
ρ_w = density of water in dredging area, lb/ft^3
D_E = displacement of dredge prior to dump, tons
D_S = displacement of dredge at start of load cycle, tons

V_E = volume in hopper prior to dump, yd^3
ρ_i = in-place density of dredged material, lb/ft^3

In Equations 1 through 4, reference is made to the "bin water" in the hopper. The bin water refers to that water which is present in the hopper just prior to the commencement of dredging sediment for each load. Typically, the hopper is not entirely empty or dry after dumping a load, and a certain volume of water is in the bottom of the hopper. That volume of water is referred to as the bin water. Calculation of the average density in the hopper, as shown in Equation 3, requires dividing the total weight of material in the hopper by the total volume of that material. If the bin water is neglected, then the calculation will be incorrect.

System Components

The monitoring system designed for this project consisted of several instrument systems, each of which monitored a different function of the dredge. The dredge functions that were monitored included the level of material in the hopper, the draft of the vessel, the density and velocity of material passing through the production meters, the ship's position, and the depth of the port and starboard dragheads. Each of these dredge functions are discussed in greater detail in the following sections.

Level of material in the hopper

The level of material in the hopper was monitored by two programmable ultrasonic sensors, one installed over each end of the hopper along the longitudinal center line of the hopper. These sensors measured the distance between the surface of the material in the hopper and the sensor. The ultrasonic sensors measure distance by using a piezoelectric transducer to send out ultrasonic waves in a series of pulses. The sound waves are emitted in the shape of a beam cone, are reflected off of the target surface (water or slurry mixture surface in the hopper), and echo back to the sensor. The distance between the sensor and the target is calculated from the time interval between the transmission of the sound waves and the return of the echo to the sensor. The sensors are fully programmable, are accurate to within ± 0.2 percent of the measuring range, compensate for temperature variations, and are capable of measuring distances over a range of 0.3 to 70 ft[1] (Lundahl Instruments 1991).

The sensors were installed on specially designed brackets extending out over each end of the hopper and were installed high enough over the maximum water level in the hopper to minimize direct contact with splashing

[1] A table of factors for converting non-SI units of measurement to SI units is found on page vii.

or spraying slurry or water. The sensor at the aft end of the hopper was mounted on a catwalk approximately 10 ft above the top of the hopper. Figures 1 and 2 show two perspectives of the ultrasonic sensor installed on the dredge over the aft end of the hopper. The sensor at the forward end of the hopper was mounted on a valve housing approximately 3 ft above the top of the hopper. Figures 3 and 4 show two views of the ultrasonic sensor installed over the forward end of the hopper. Figure 5 provides an overall view of the hopper looking forward from near the aft end of the hopper.

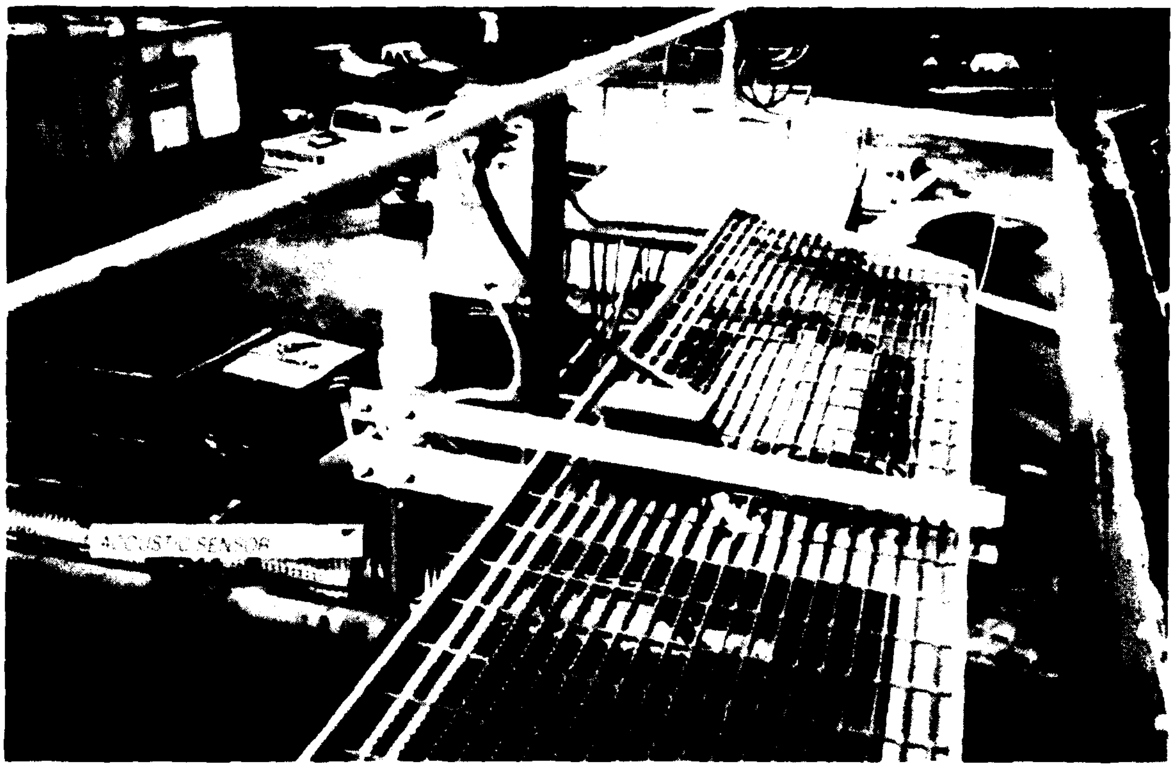

Figure 1. Closeup view of acoustic sensor at aft end of hopper

Draft of vessel

The draft of the vessel was monitored by inserting pressure sensors into the existing bubbler line system, which measured the draft at two bubbling points located in the keel of the ship, one near the dredge's forward perpendicular and one near the dredge's aft perpendicular. The bubbler system was designed such that the draft of the ship at any time produced a pressure in the bubbler lines equivalent to the hydrostatic pressure at the bubbling points in the keel of the ship. A constant volume of air was forced down through the bubbler lines. The pressure required to force that air through the system and out the bubbling points was equal to the hydrostatic pressure at the bubbling points below the water surface. Thus, the system measured the distance from the keel of the ship to the water surface, or the draft of the vessel.

Figure 2. Acoustic sensor at aft end of hopper

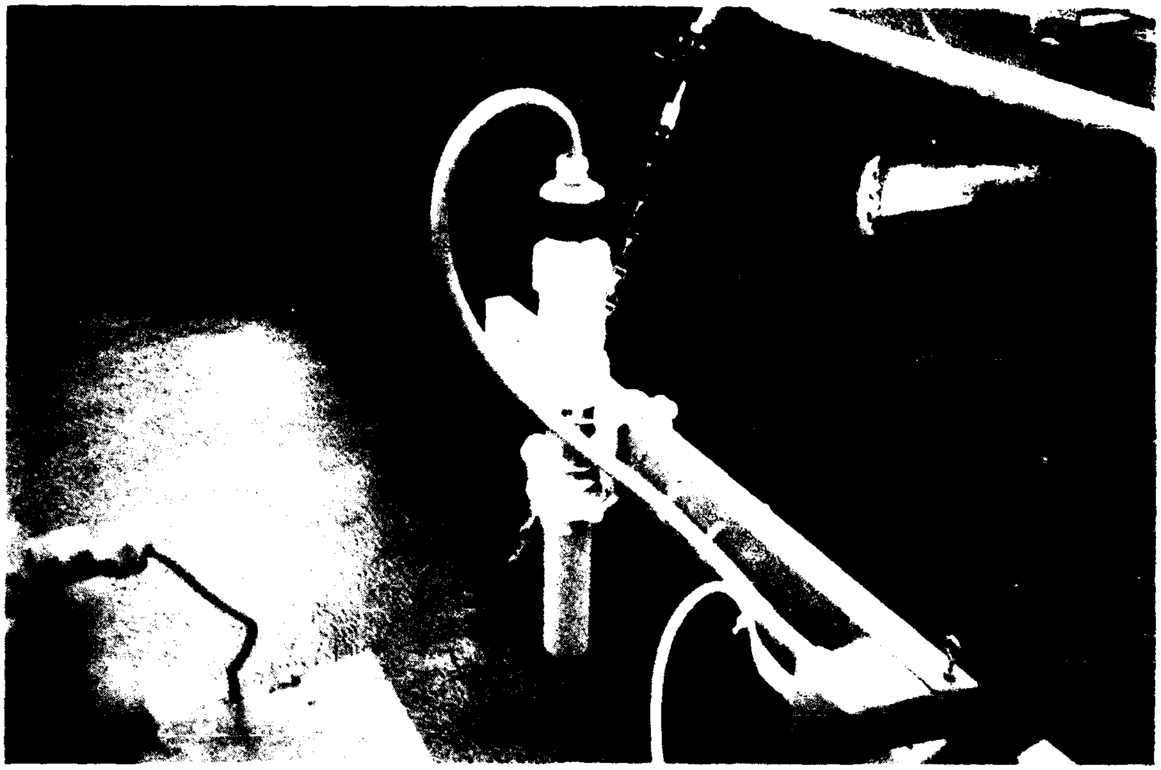

Figure 3. Closeup view of acoustic sensor at forward end of hopper

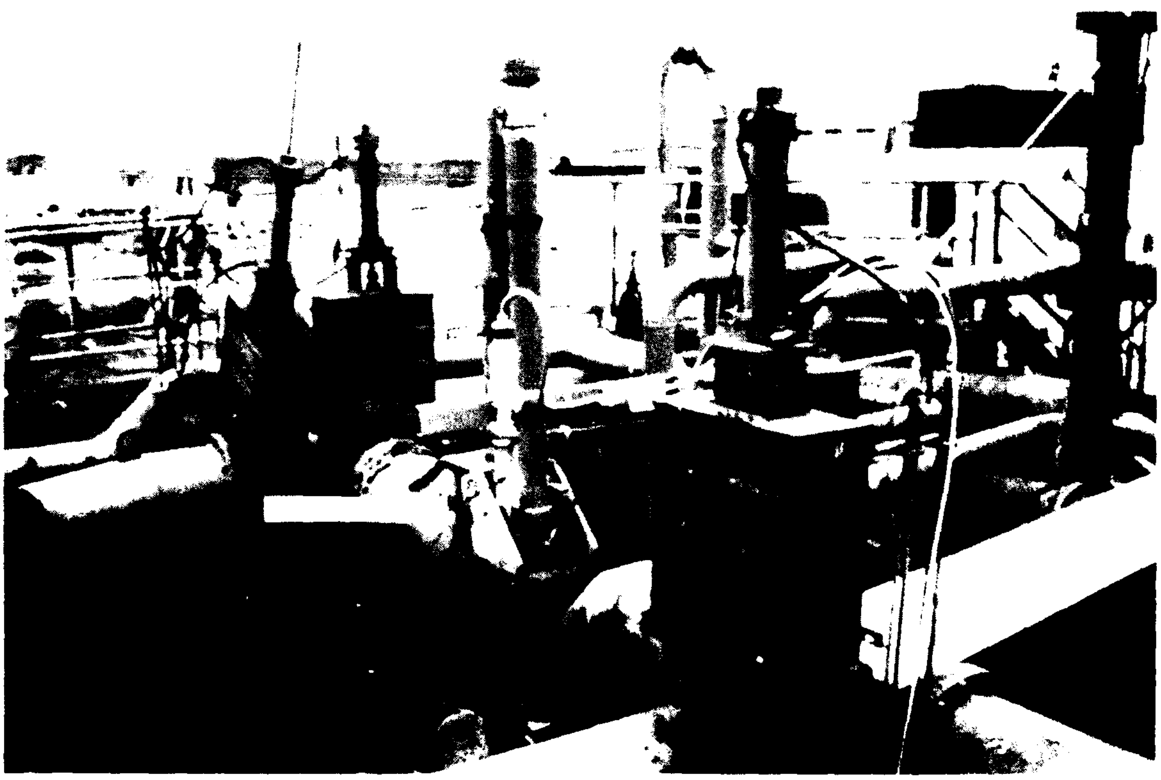

Figure 4. Acoustic sensor at forward end of hopper

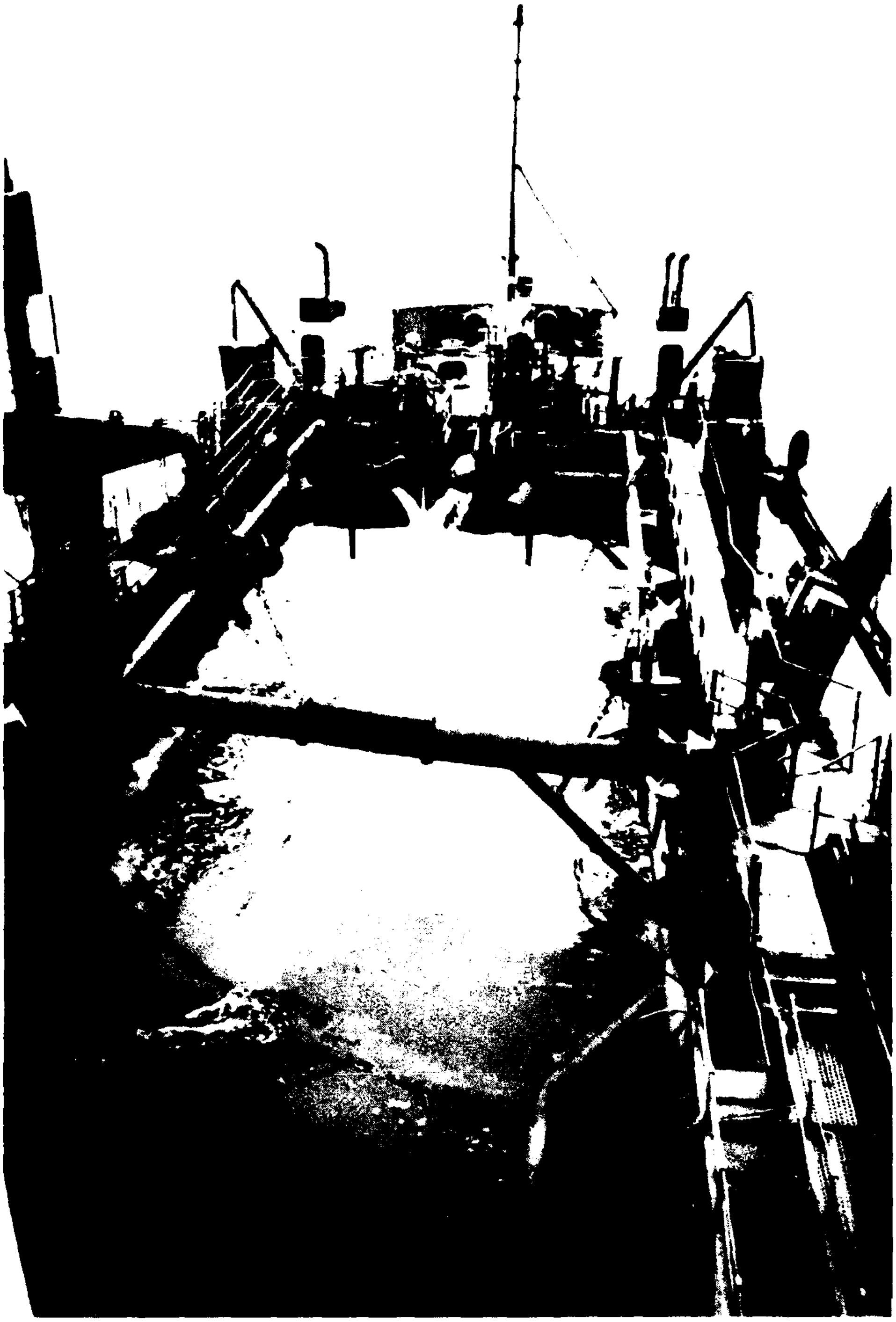

Figure 5. Hopper

The pressure sensors in the forward and aft bubbler lines were placed inside the load displacement recorder cabinet (Figure 6). In each air line, the pressure was measured by connecting a Consolidated Electrodynamics Corporation Type 4-312 Pressure Pickup. This is shown in Figure 7, where the two white cables with tags attached are leading from the pressure pickups. The sensing elements of the pressure transducers were composed of unbonded strain gauge windings connected in a four-arm bridge. Pressure against the diaphragm produced a displacement of the sensing element, changing the resistance of the active arms and causing an electrical output proportional to the applied pressure (Consolidated Electrodynamics Corporation 1956). The pressure transducers installed had a pressure range of 0-25 lbf/in.^{2} The draft of the vessel at the forward and aft bubbling points was determined by converting the measured pressure in the air lines from pounds per square inch to feet of water using the density of the water in the location where the dredge was operating. For example, if the pressure in the air line was measured at

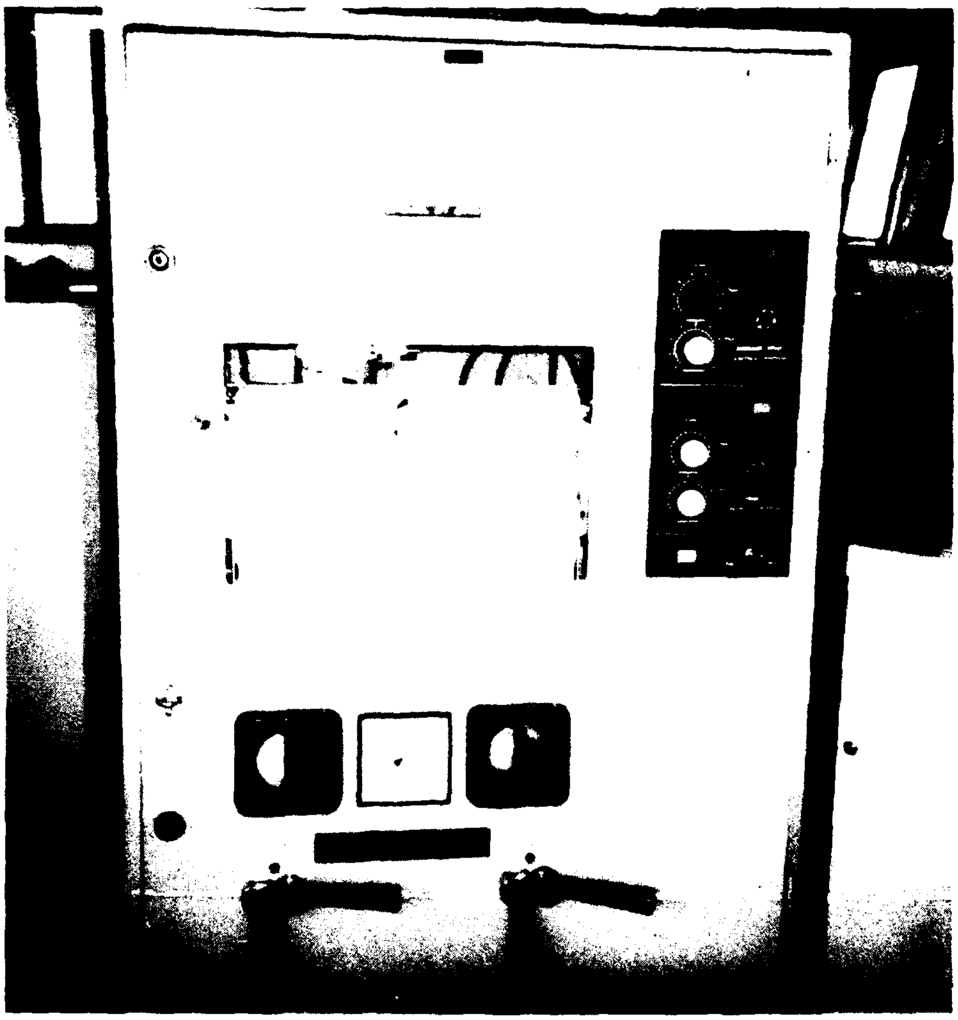

Figure 6. Load displacement recorder cabinet

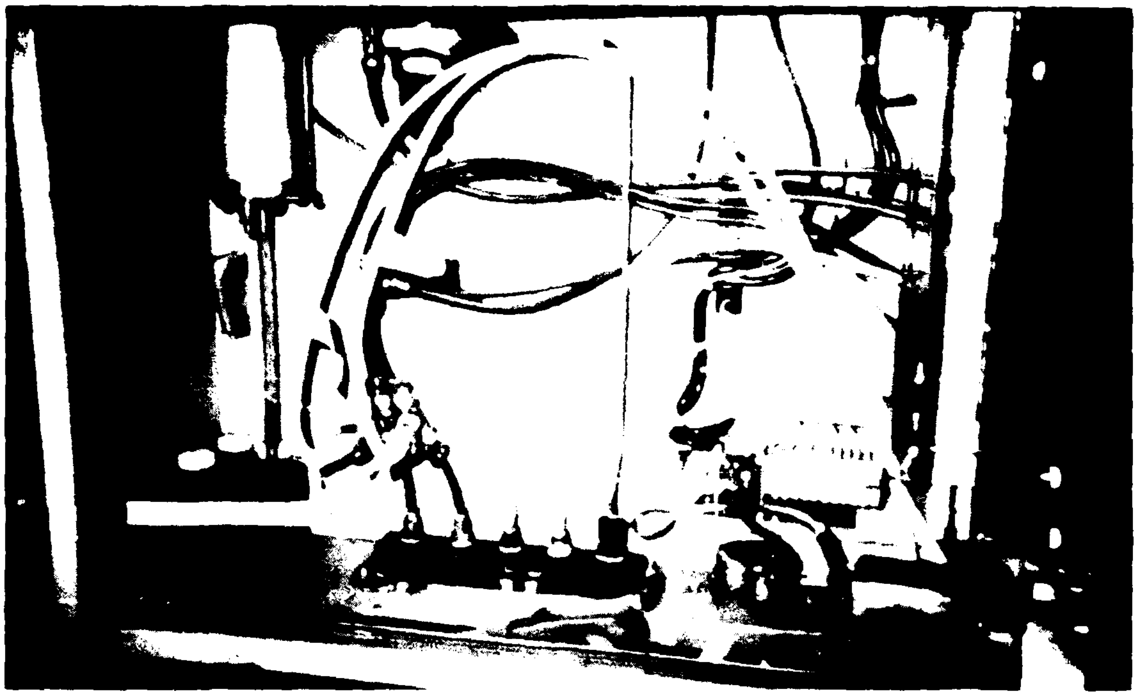

Figure 7. Pressure cells in air lines

7.0 lbf/in.^{2} and the specific weight of the water was 63.7 lbf/ft^3, then the draft was determined as follows:

$$\text{Pressure} = 7.0 \text{ lbf/in.}^2 * 144.0 \text{ in.}^2/\text{ft}^2 = 1{,}008.0 \text{ lbf/ft}^2 \tag{5}$$

$$\text{Draft} = (1{,}008.0 \text{ lbf/ft}^2) / (63.7 \text{ lbf/ft}^3) = 15.8 \text{ ft} \tag{6}$$

Production meters

The dredge was equipped with density and velocity meters on both the port and starboard drag arms to measure the density and velocity of the slurry mixture being pumped. The density of the slurry was measured with nuclear density gauges, and the velocity was measured with magnetic flowmeters. For the monitoring system, signals from those existing gauges and meters were obtained, and the density and velocity of the slurry being pumped through each drag arm were monitored and recorded.

Ship's position

The position of the dredge was provided by a Del Norte positioning system. Output from this system provided northing and easting coordinates for the position of the vessel, which were recorded by the monitoring system.

Draghead depth

The dredge was equipped with depth indicators for the port and starboard dragheads. The depth indicators for the dragheads consisted of a bubbler system like the system used to measure the draft of the vessel, but with the bubbling points located on each draghead. As with the draft measurement system, pressure taps were placed in the air lines for the port and starboard dragheads. The air pressure in those lines was measured using Consolidated Electrodynamics Corporation Type 4-312 Pressure Pickups, and the depth of the dragheads was calculated by converting the air pressure in the bubbler lines into feet of water.

Data Acquisition

The output from all sensors was recorded continually every 5 seconds using a laptop computer installed on the dredge specifically for this project. The data acquisition software was configured such that a binary data file was created at midnight each day that contained the data for the previous 24-hour period. Ten channels of data were recorded, in addition to the time and the location coordinates. Table 1 provides a list of the ten data channels. Recording the time, location coordinates, and ten data channels every 5 seconds throughout the day resulted in a binary data file each day containing 933,120 bytes. The hard disk on the computer was capable of continuously recording data for approximately 63 days before the storage capacity on the disk was full.

A program was written to convert each binary data file into two ASCII output files, one containing the location coordinates and another containing the 10 channels of data listed in Table 1. The program also converted the raw data, which was typically recorded as a voltage or a 4-20 mA signal from the various sensors in the monitoring system, into the appropriate engineering units, also shown in Table 1.

Figures 8 through 17 are examples of the data recorded on each of the channels listed in Table 1. The figures are plots of the data versus time for one typical load from the Chincoteague Inlet project over a period of approximately 2 hours, from 11.5 hours (11:30 a.m.) to just after 13.5 hours (1:30 p.m.) on 16 March 1993. As can be seen in Figures 8, 9, 10, and 11, the draft and level of material in the hopper were at minimums just after 11:30 a.m., indicating that a load had just been dumped. Immediately thereafter, a small amount of bin water returned to the hopper, and dredging commenced at approximately 11:45 a.m. Dredging continued until shortly after 1:00 p.m., some water was then allowed to drain off the top of the hopper, the load was dumped just after 1:30 p.m., and a new cycle started. Figures 12 and 13 are plots of the starboard and port draghead depths showing that the dragheads were raised and lowered several times during that load. Figures 14 through 17 show the production meter data, slurry density, and

Table 1
Data Acquisition Channels

Data Acquisition Channel	Data Acquired	Engineering Units
1	Aft draft	ft
2	Forward draft	ft
3	Aft level in hopper	ft
4	Forward level in hopper	ft
5	Starboard draghead depth	ft
6	Port draghead depth	ft
7	Density in starboard drag arm	g/cm^3
8	Velocity in starboard drag arm	ft/sec
9	Density in port drag arm	g/cm^3
10	Velocity in port drag arm	ft/sec

velocity for the starboard and port drag arms. Figures 18 and 19 are plots of the dredge's position during that same period. Indicated in Figure 18 are the corners of the designated dump site for the Chincoteague Inlet project, and in Figure 19 are several center-line stations along the channel being dredged.

Data Reduction

Calculating the bin measure load and analyzing the amount of solids retained in the hopper during the overflow process require knowledge of the volume of material in the hopper, the total displacement of the vessel, and the cumulative weight of solids as indicated by the production meters. As seen in Table 1, none of the data acquired by the monitoring system provides that information directly. Therefore, the information on the level in the hopper, draft, and density and velocity in the drag arms must be converted from the initial data into volume of material in the hopper, total displacement of the vessel, and cumulative weight of solids pumped. The data conversion for each of these is described in the following paragraphs.

Volume of material in hopper

As previously discussed, the acoustic sensors over the hopper measured the distance from the sensor to the water or slurry surface in the hopper. That distance needed to be converted into an average depth of material in the hopper and then into volume of material in the hopper. To accomplish this, the depth of material in the hopper below each sensor was determined by

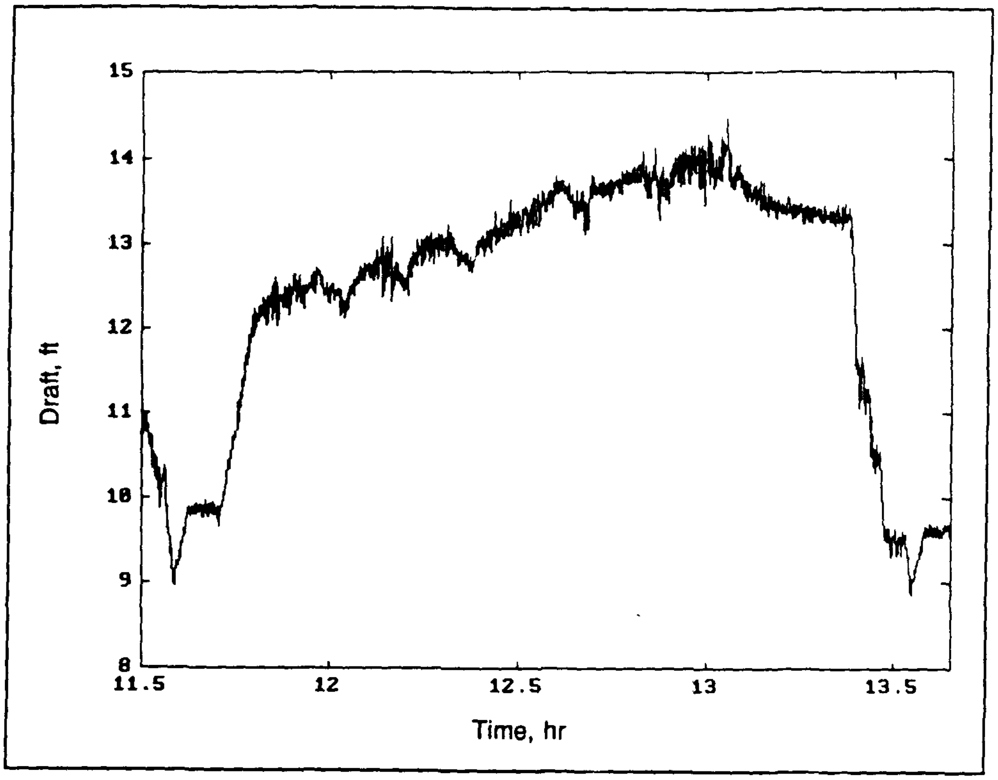

Figure 8. Aft draft versus time

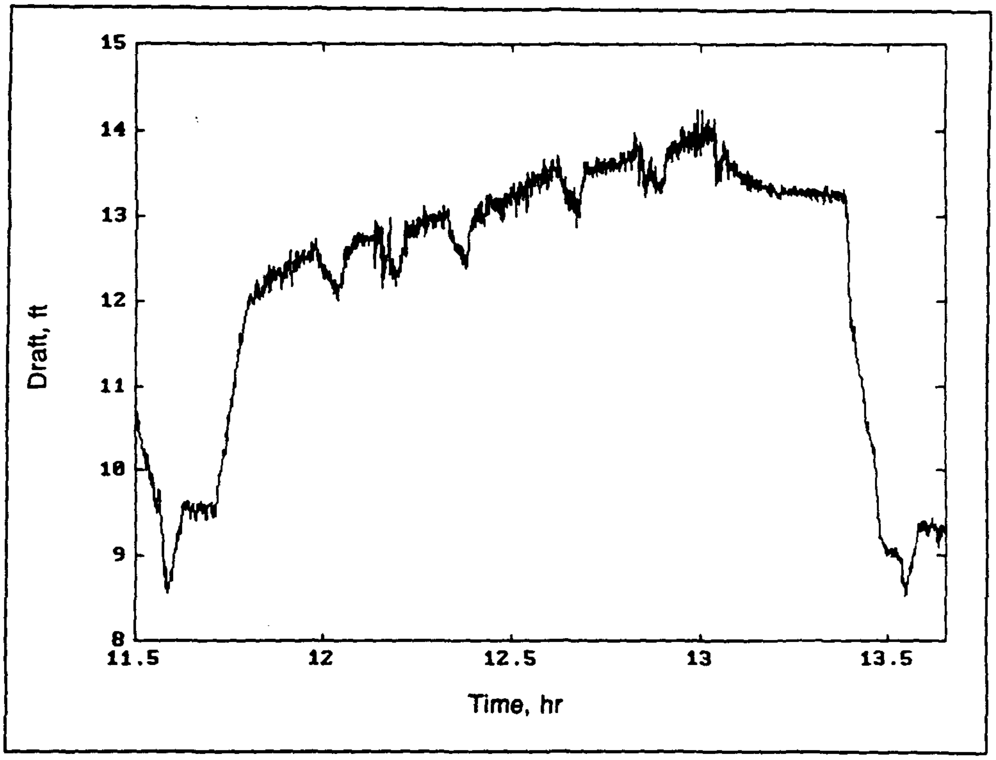

Figure 9. Forward draft versus time

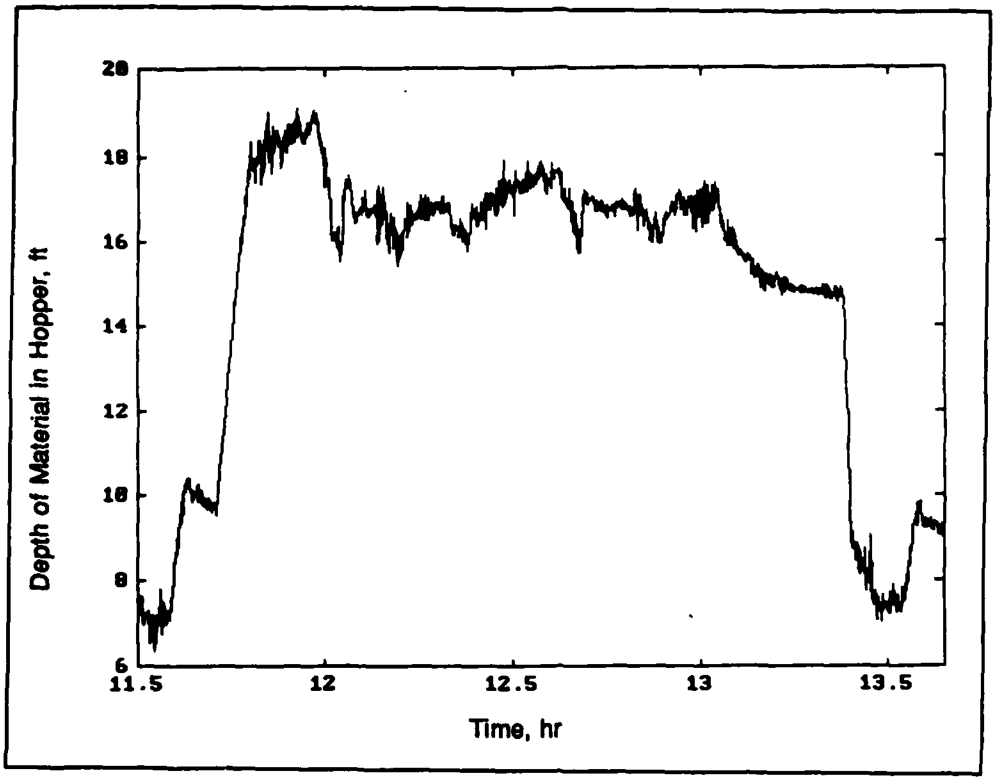

Figure 10. Depth of material in aft end of hopper versus time

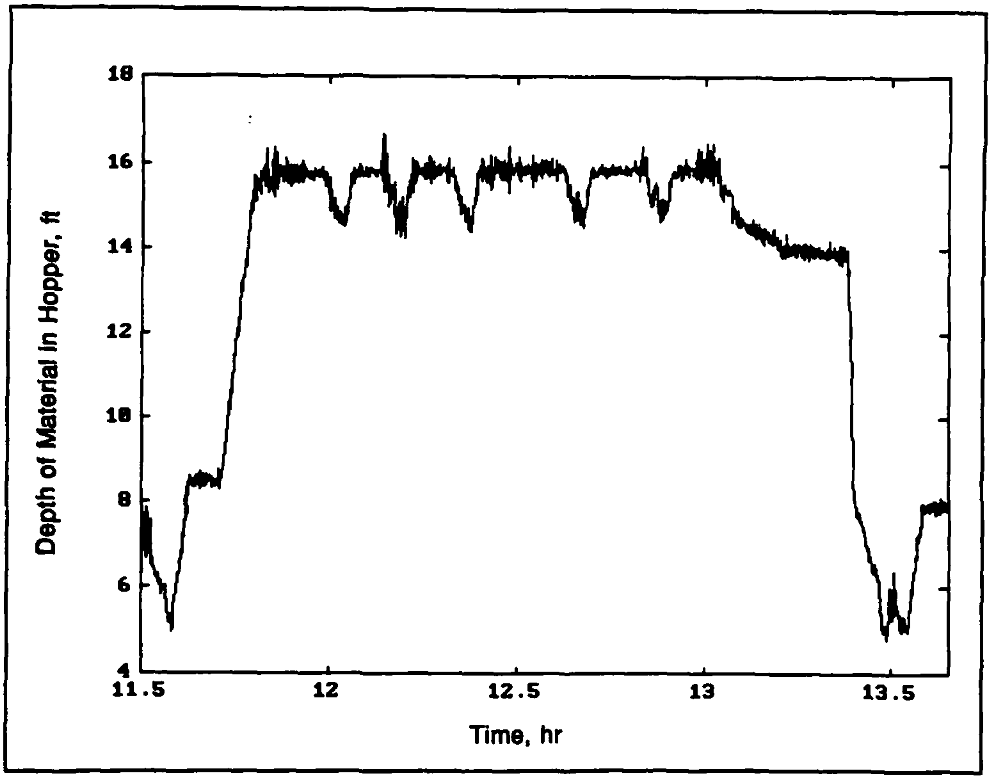

Figure 11. Depth of material in forward end of hopper versus time

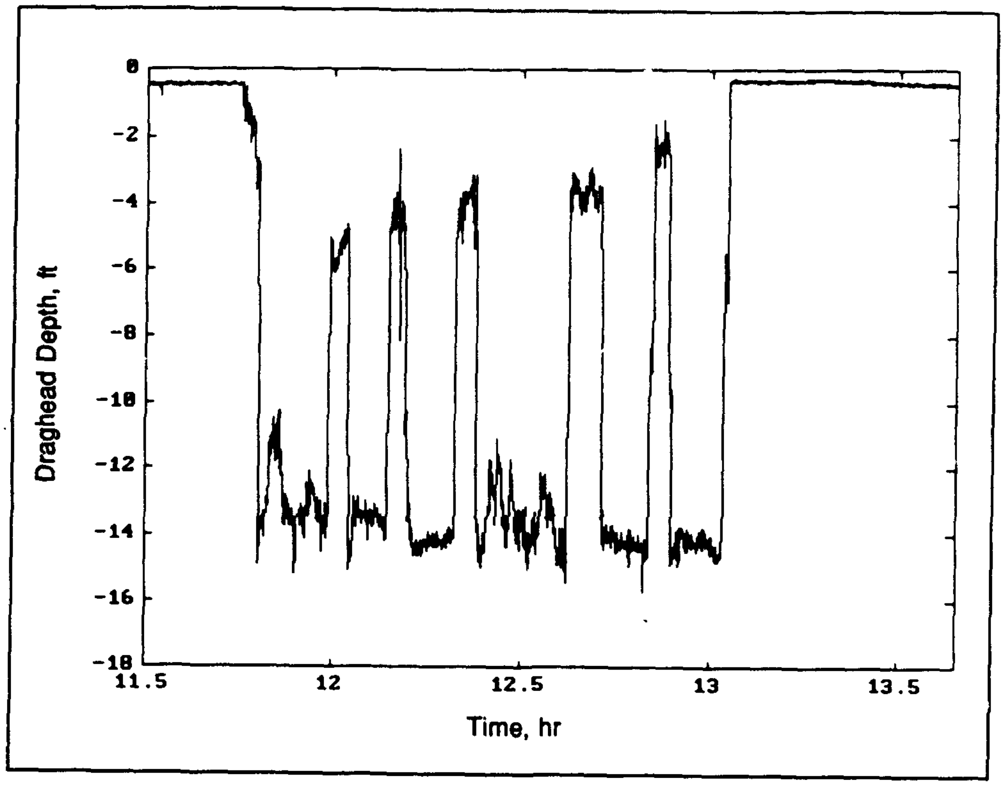

Figure 12. Starboard draghead depth versus time

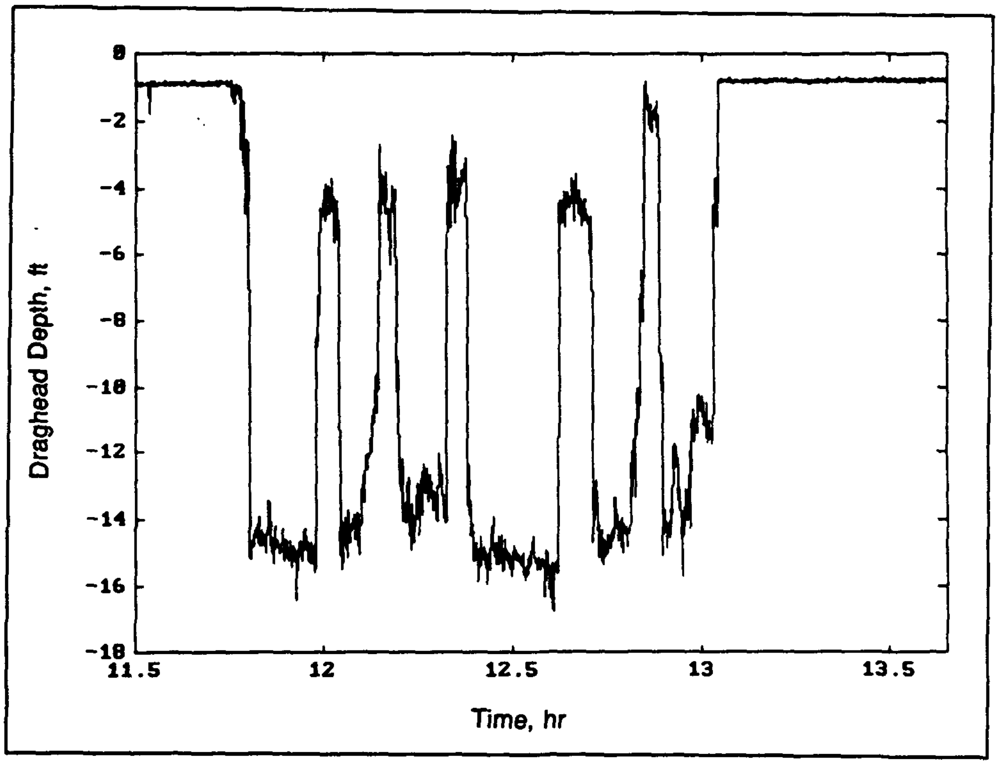

Figure 13. Port draghead depth versus time

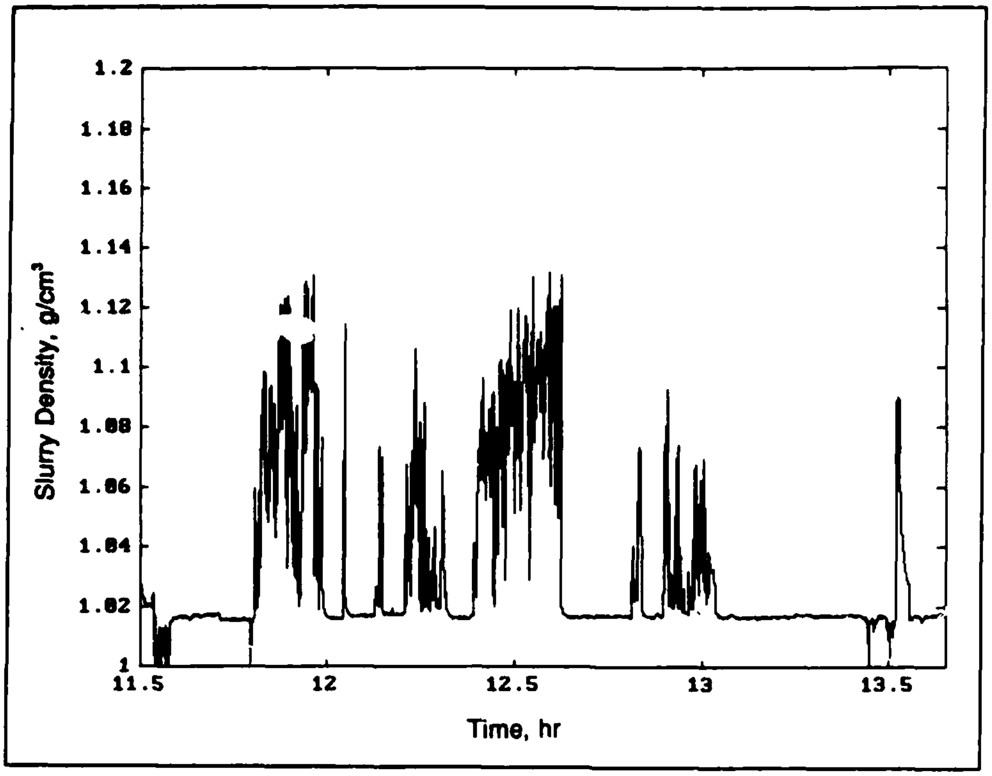

Figure 14. Slurry density in starboard drag arm versus time

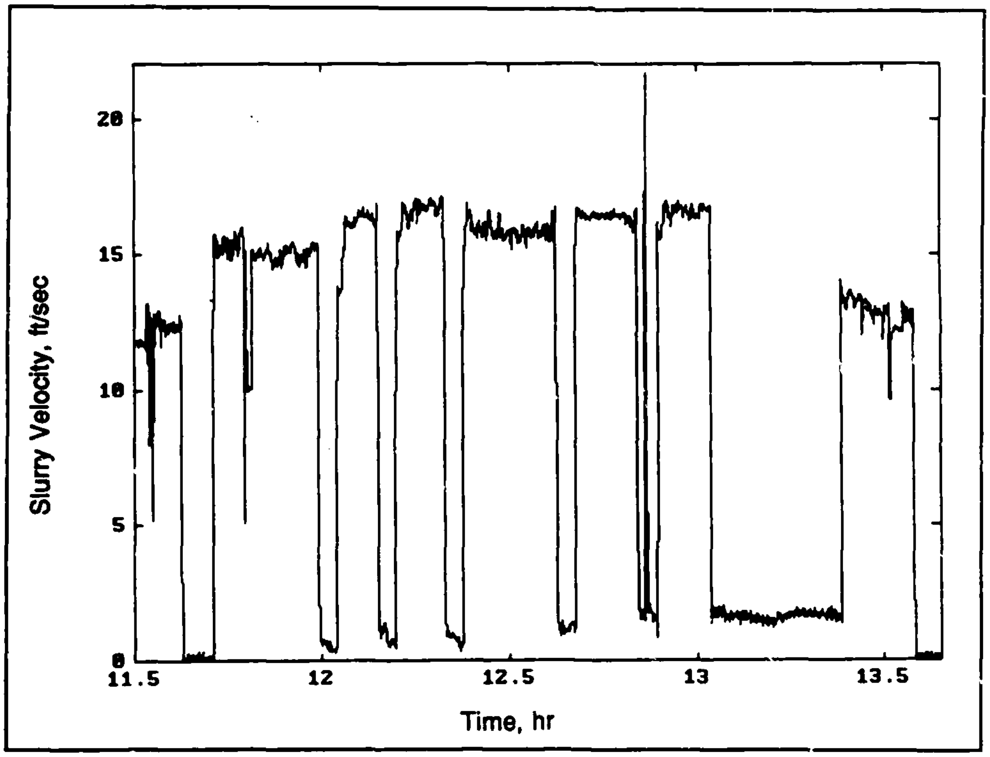

Figure 15. Slurry velocity in starboard drag arm versus time

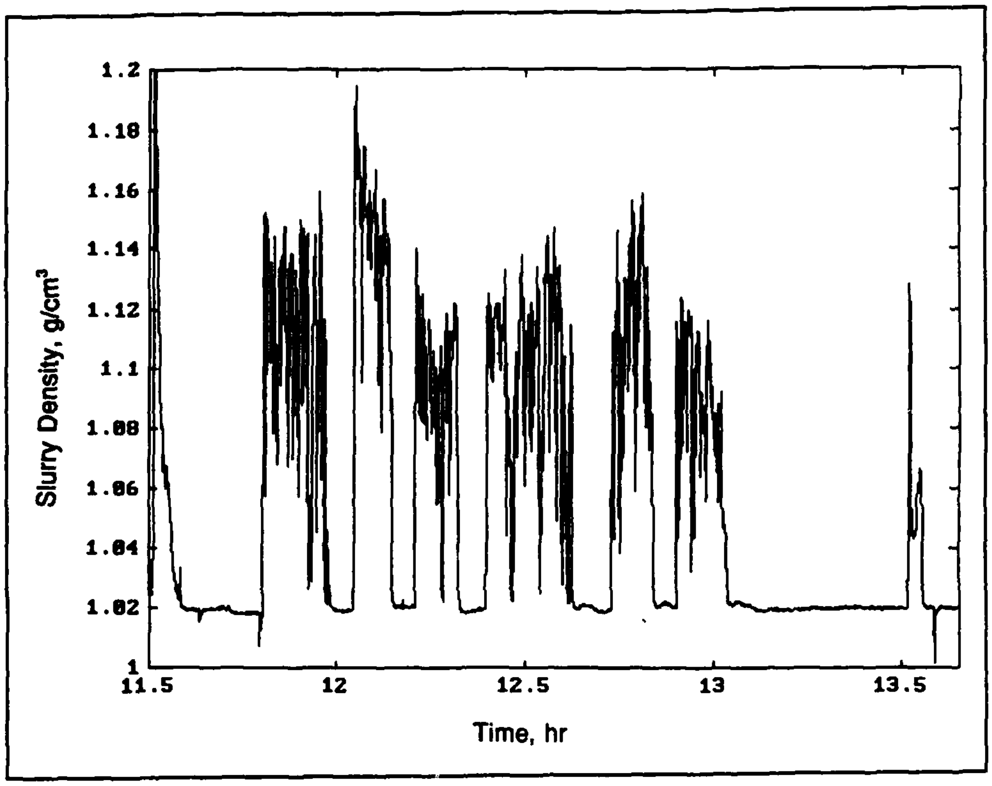

Figure 16. Slurry density in port drag arm versus time

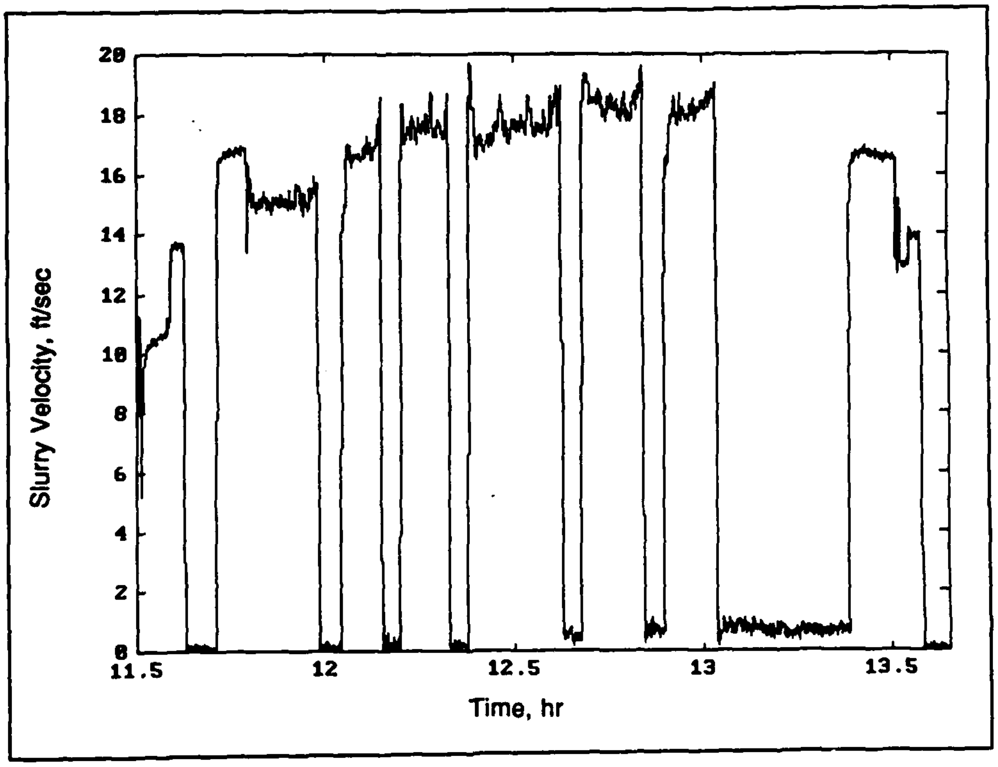

Figure 17. Slurry velocity in port drag arm versus time

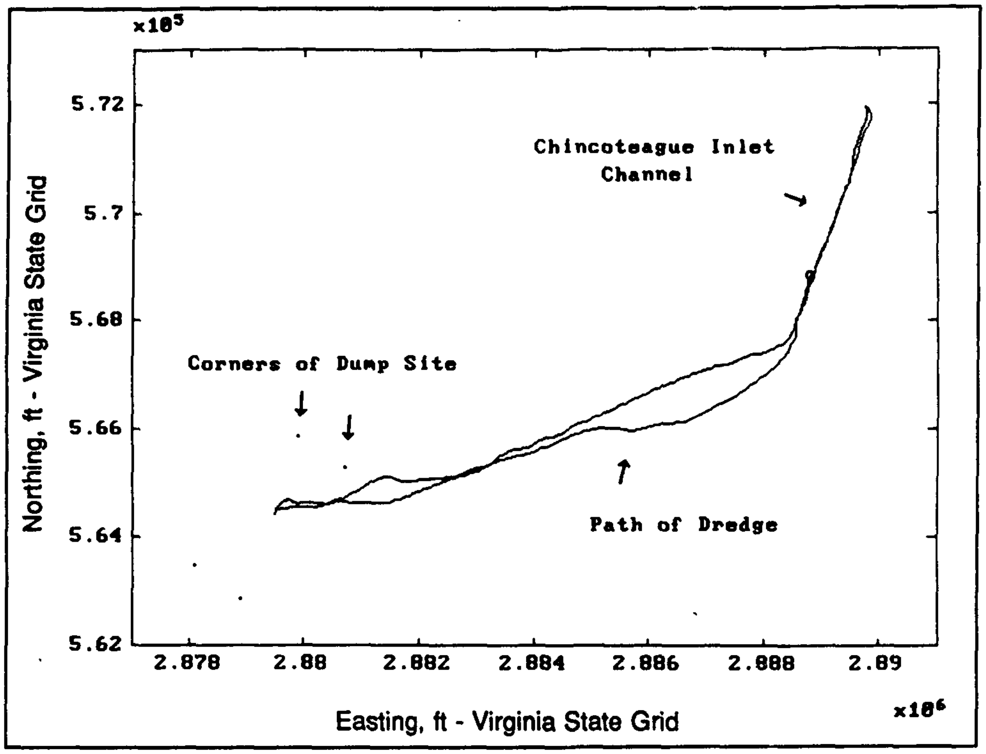

Figure 18. Dredge position (northing and easting) during a typical load cycle

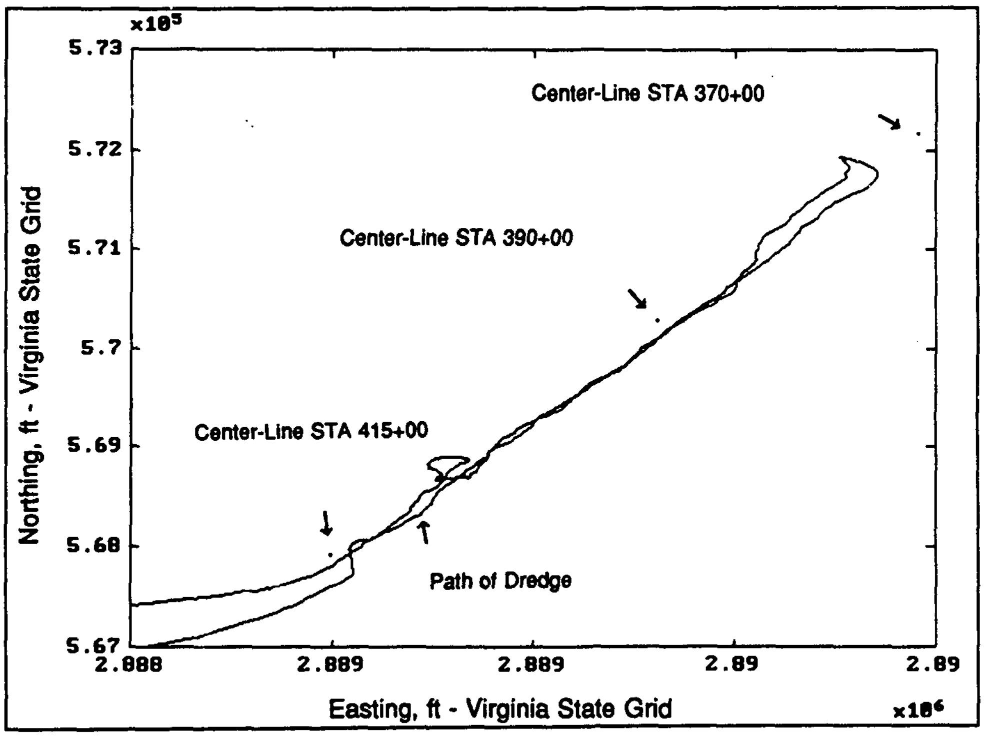

Figure 19. Dredge position (northing and easting) in the channel during a typical load cycle

subtracting the measured distance between the sensor and the water surface from the total distance between the sensor and the bottom of the hopper:

$$D = TD - MD \quad (7)$$

where

D = depth of material in the hopper, ft
TD = total distance from acoustic sensor to hopper bottom, ft
MD = measured distance from sensor to water surface, ft

(Note that the data plotted in Figures 10 and 11 had already been converted this way such that the plots show the level of material in the hopper as opposed to the distance from the acoustic sensor to the top of the material in the hopper.)

The resulting values were then converted into hopper volume through the use of the ullage table for the dredge. The ullage table provides the capacity of the hopper, in cubic yards, for any given depth of material in the hopper. Using that ullage table information, a plot of hopper volume versus depth in the hopper was made, a curve was fit to that plot, and the equation of the curve was determined. That equation provided a value for hopper volume in cubic yards for a given value of average hopper depth. Thus, the data from the two acoustic sensors were converted into depth of material, the average depth in the hopper was calculated, and a hopper volume was computed for that average depth. Figure 20 is a plot of the volume of material in the hopper versus time for the same period covered in Figures 8 through 19.

Vessel displacement

To determine the weight of material in the hopper for the bin measure load calculation, the value required is not the draft of the ship, but the weight, or displacement, of the ship. Thus, the draft values had to be converted into displacement. This was accomplished through the use of the hydrostatic curves of form for the vessel. The hydrostatic curves of form include many curves that describe the characteristics of the vessel, among which is a data curve that relates draft and displacement. A curve fit equation was determined for that draft versus displacement curve. The resulting equation provided displacement, in tons, for any given values of fore and aft draft. Figure 21 is a plot of the vessel displacement for the same period in Figures 8 through 20.

Cumulative weight of solids

To analyze the amount of solids retained in the hopper during the overflow process, the weight of solids pumped during overflow was compared to the weight of solids retained during overflow. The density meter provided the density of material in the drag arm, and the flow meter provided the velocity

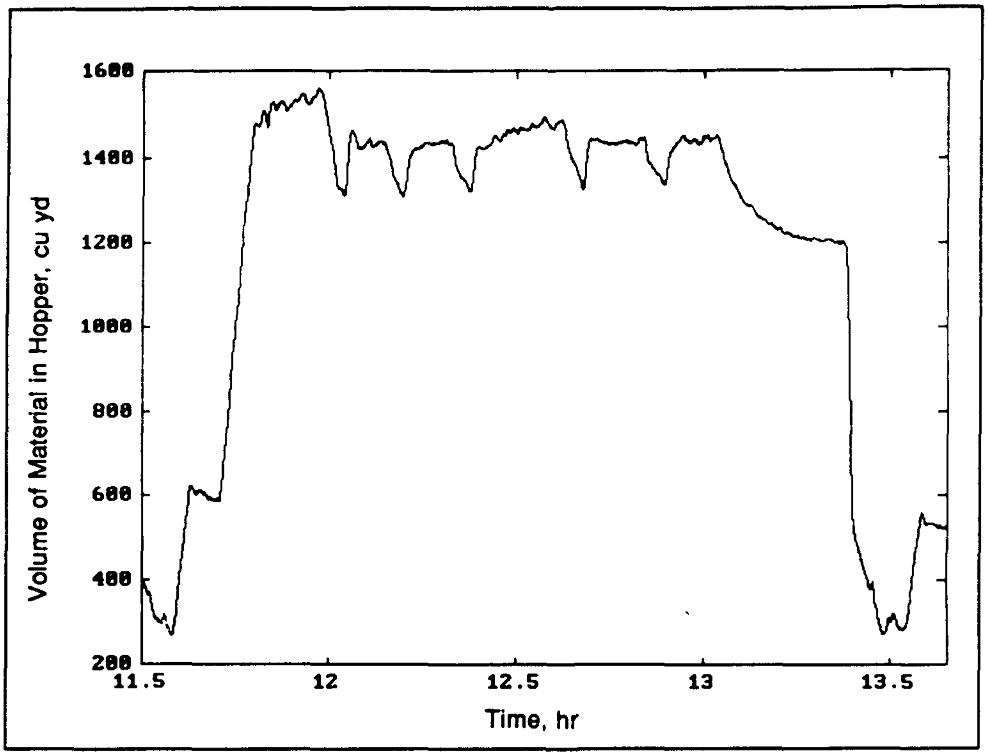

Figure 20. Volume of material in hopper versus time

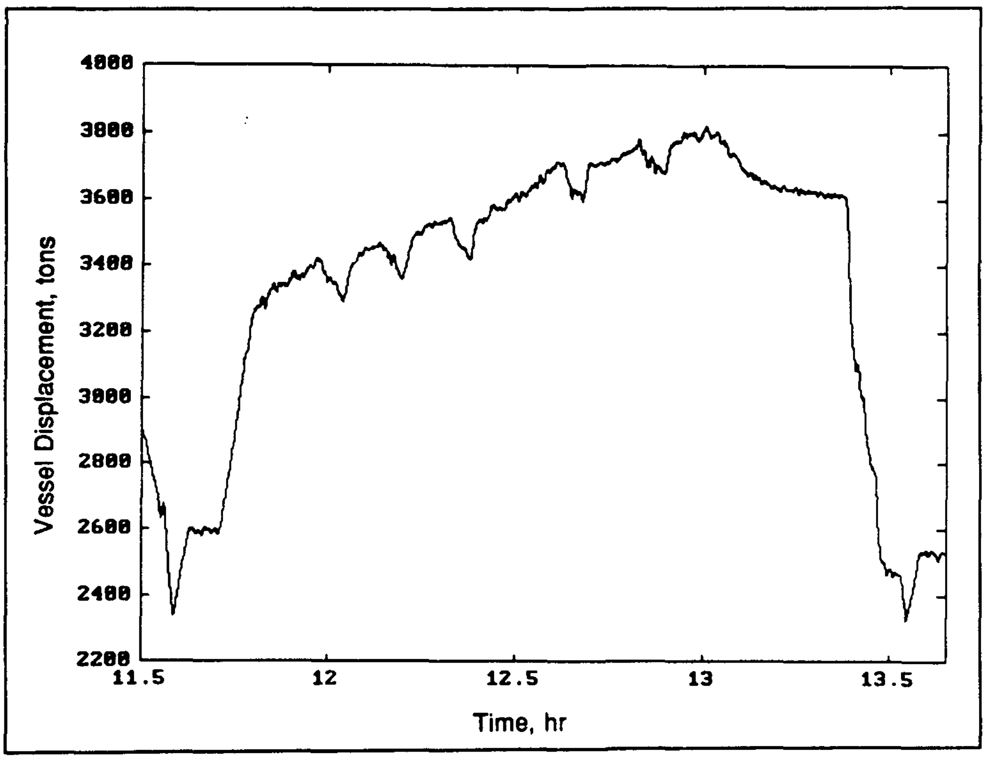

Figure 21. Vessel displacement versus time

of the material in feet per second. These data were recorded every 5 seconds. The cumulative weight of solids was calculated as follows.

$$M_s = \frac{\rho_m - \rho_w}{\rho_s - \rho_w} * \rho_s * 62.4 * V_m * A * T \tag{8}$$

where

M_s = solids mass production, lb
ρ_m = density of material in drag arm, g/cm^3
ρ_w = density of interstitial water, g/cm^3
ρ_s = density of solids, g/cm^3
V_m = velocity of mixture in drag arm, ft/sec
A = cross-sectional area of drag arm suction pipe, ft^2
T = time interval between measurements, sec

For example, if the density of the interstitial water was measured as 1.007 g/cm^3, the density of the solids was 165.36 lb/ft^3, the cross-sectional area of the suction pipe was 1.767 ft^2, the time interval between measurements was 5 seconds, the average density of material in the drag arm measured by the density meter over the 5-second interval was 1.3 g/cm^3, and the average velocity of material in the drag arm measured by the flow meter was 15.0 ft/sec, then the weight of solids over that 5-second interval would be:

$$\begin{aligned} W_s &= \left[\frac{1.3\ g/cm^3 - 1.007\ g/cm^3}{2.65\ g/cm^3 - 1.007\ g/cm^3}\right] * \\ &\quad 165.35\ lb/ft^3 * 15.0\ ft/\text{sec} * 1.767\ ft^2 * 5.0\ \text{sec} \\ &= 3{,}908.0\ lb \end{aligned} \tag{9}$$

Figure 22 plots the cumulative weight of solids pumped during the same period covered in the previous figures. Note that the weight of cumulative solids in Figure 22 is expressed in tons to correspond with the unit of measurement for the total displacement of the vessel.

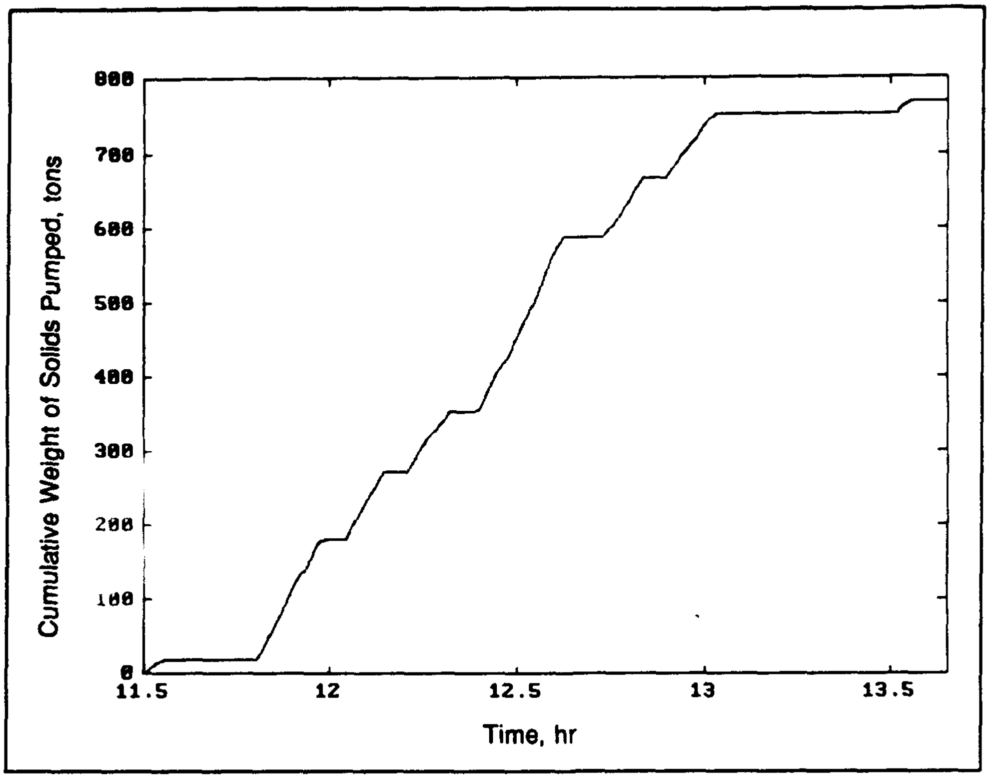

Figure 22. Cumulative weight of solids pumped versus time

3 Dredging Project Monitoring

Two dredging projects were monitored for this study, maintenance dredging at Chincoteague Inlet, Virginia, and maintenance dredging in the Norfolk Harbor channel, Virginia. The contracts for those projects were awarded to the North American Trailing Company (NATCO). The monitoring system was installed aboard the NATCO dredge *Northerly Island,* which performed the dredging work. The *Northerly Island*, a split hull dredge, has an overall length of 205 ft with an overall beam of 48 ft and two 18-in. drag arms. The dredge generally drafts from 5 to 15 ft. The pumping system consists of two 625-hp pumps, and the dredge has a hopper capacity of 2,178 yd^3 (U.S. Army Corps of Engineers 1985).

The Chincoteague Inlet and Norfolk Harbor projects were two separate dredging projects, and each project presented very different conditions under which to evaluate the usefulness and effectiveness of the monitoring system. Although the monitoring system acquired the same type of information during each project, the primary focus of the monitoring system on the Chincoteague Inlet project was to calculate the bin measure production for each load, while the retention of solids during the overflow process was of primary interest for the Norfolk Harbor project.

Chincoteague Inlet

Chincoteague Inlet is located at the entrance to Chincoteague Bay between Assateague Island and Chincoteague Island along the northern coast of Virginia. Figure 23 is a vicinity map for Chincoteague Inlet showing its location with respect to Norfolk, VA, and Chesapeake Bay, and Figure 24 is a location map showing the dredging area (shown as "Location of Survey" on the map) and disposal site (shown as "Placement Area" on the map) near Chincoteague Inlet.

Chincoteague Inlet is subject to fairly rapid and unpredictable shoaling conditions that make bathymetric surveys unreliable. Because of these conditions, the maintenance dredging at Chincoteague is paid by bin measure. A predredging survey is performed to provide an estimate of the extent of shoaling, and a postdredging survey is performed to verify that the channel is

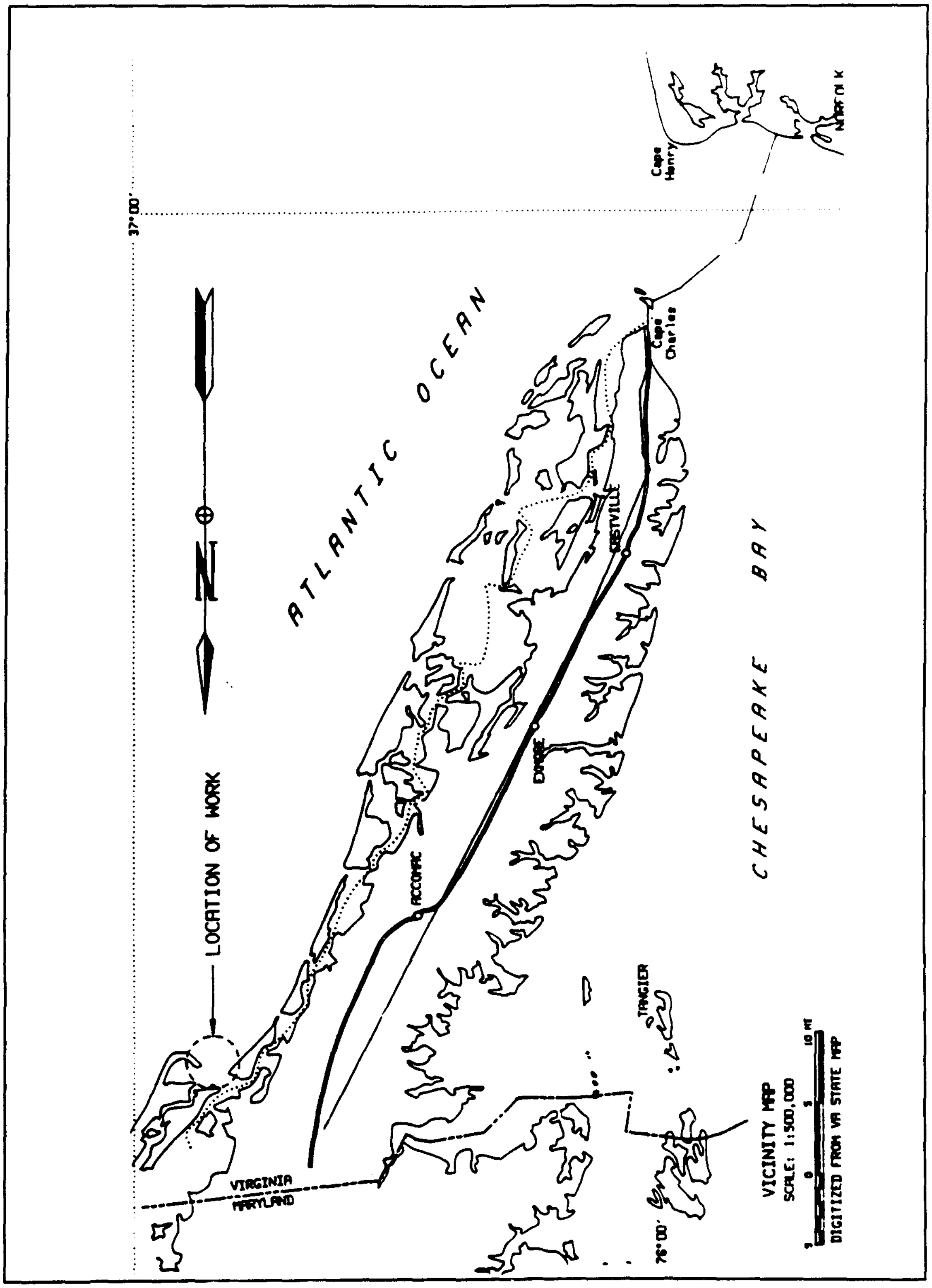

Figure 23. Vicinity map for Chincoteague Inlet, Virginia

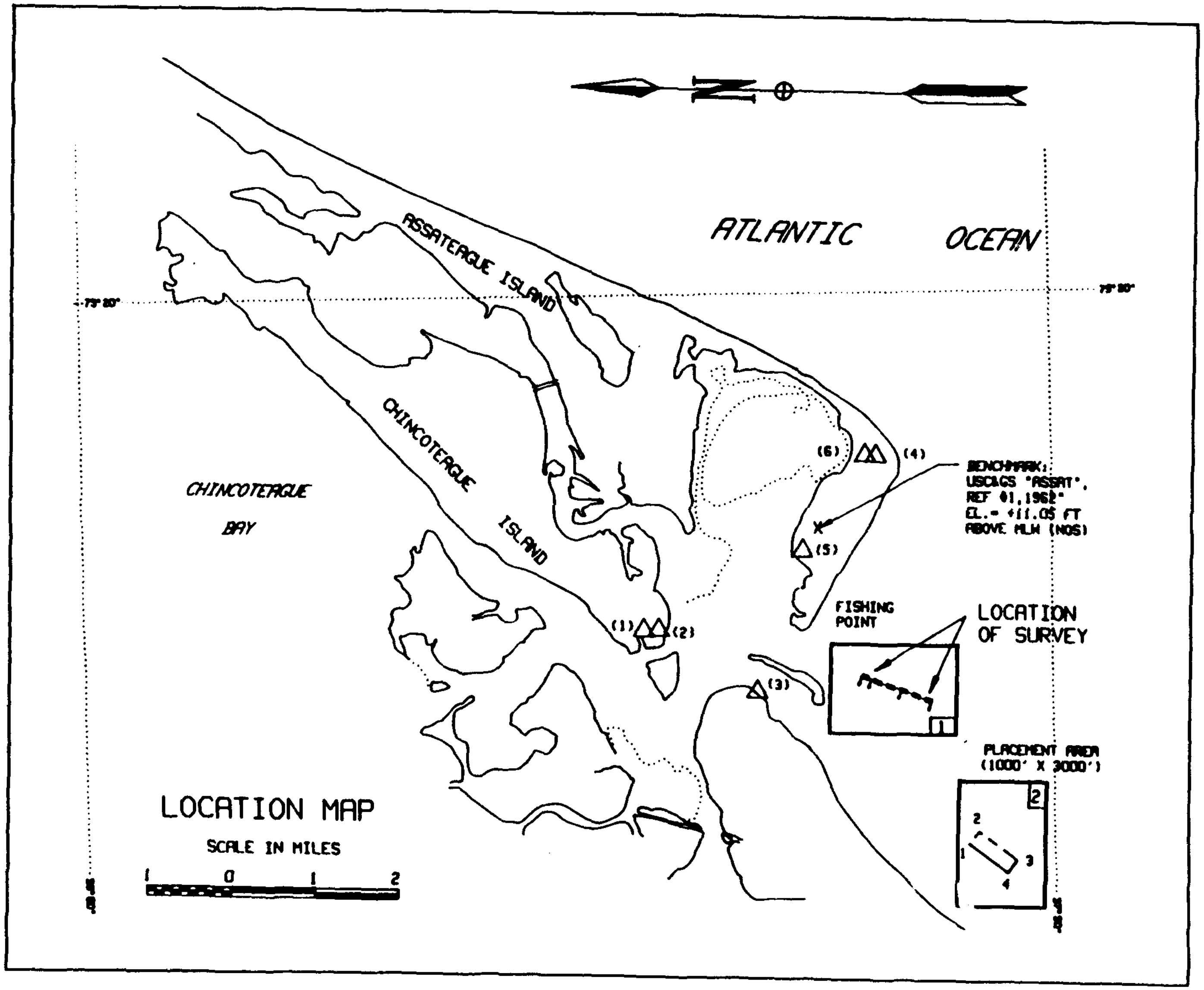

Figure 24. Location map for Chincoteague Inlet, Virginia

navigable; but payment to the contractor is not based upon those surveys. The material in the inlet is primarily fine sand with less than 5 percent fines and has an average in-place specific weight of 121.9 lbf/ft^3, as determined by a series of nuclear density measurements taken in the channel.

The monitoring system was installed aboard the dredge *Northerly Island* during a 3-day period from 2 March through 4 March 1993. Dredging at Chincoteague Inlet began on 6 March 1993, and was completed on 18 March 1993. The estimated volume of material removed from the channel was approximately 112,000 yd^3 as reported by the contractor.

Bin measure load calculations

As discussed previously, the process of calculating the bin measure load requires the determination of several variables: the volume of material in the hopper and the vessel displacement at the start of the load cycle, the volume of material in the hopper and the vessel displacement at the end of the load cycle, the density of the interstitial water, and the estimated in-place density of the material being dredged. Once those values are determined, then the bin measure load can be calculated using the procedures previously set forth.

For the Chincoteague Inlet project, the density of the interstitial water was determined by measuring the density of five water samples that were randomly taken through the duration of the project. The density of those samples ranged from 1.019 g/cm^3 to 1.021 g/cm^3 with the average being 1.020 g/cm^3 A series of six nuclear density probe measurements of the sediment were taken in the channel. The in-place sediment density measured by the probe ranged from 1.939 g/cm^3 to 1.964 g/cm^3 with the average being 1.953 g/cm^3 Based upon those nuclear density probe measurements, the average specific weight of the in-place material in Chincoteague Inlet was taken as $(1.953\ g/cm^3) * [(62.4\ lbf/ft^3)/(1\ g/cm^3)] = 121.9\ lbf/ft^3$

The next step in calculating bin loads was to plot the data for both the vessel displacement and for the volume of material in the hopper. From those plots, the beginning and end of each load was identified and the corresponding vessel displacement and volume of material in the hopper were determined. Figure 25 is a plot of both the vessel displacement and volume of material in the hopper versus time for a typical day during the Chincoteague Inlet project, 16 March 1993. Note that the vessel displacement is given in tons while the volume of material in the hopper is given in cubic yards. Also indicated in Figure 25 are two specific loads, "Load 120" and "Water Test." Load 120 was a typical load for which sample calculations were performed to determine the bin measure production, and the water test will be discussed in the following section.

The scale of Figure 25 makes it impossible to accurately determine where each load starts and ends, so each load must be isolated to provide a plot with the necessary detail. Such plots are shown in Figure 26, which is the volume

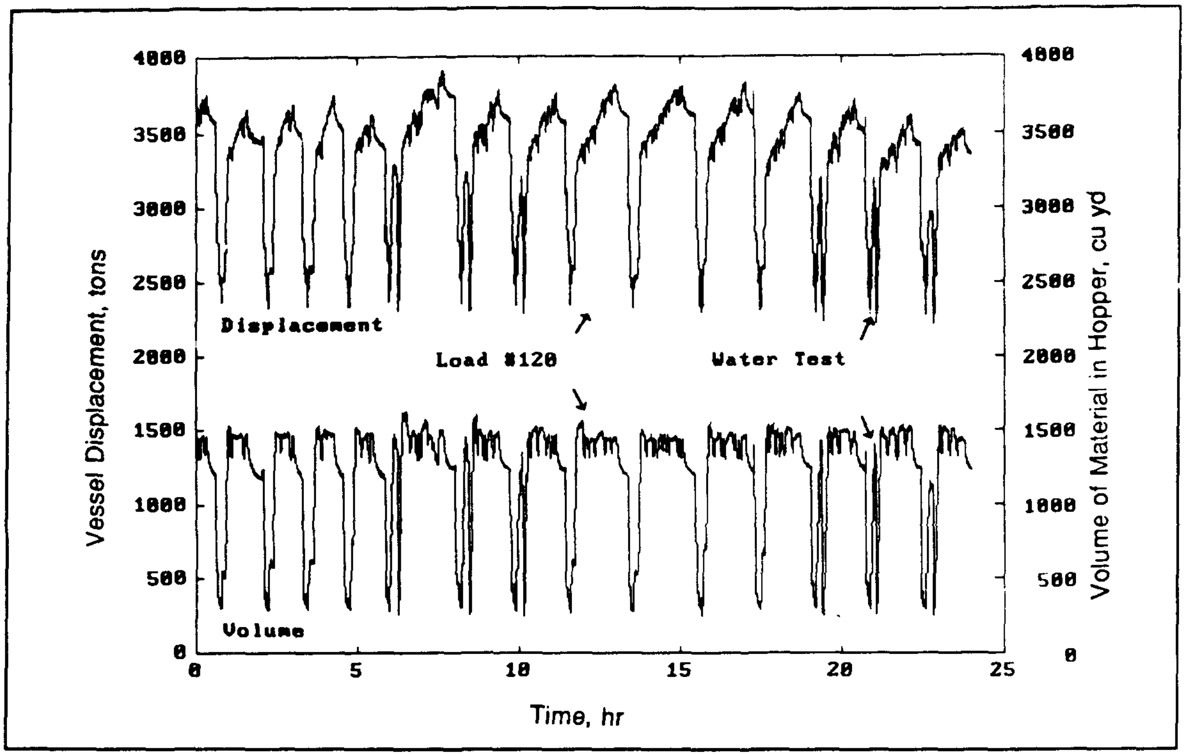

Figure 25. Volume of material in hopper and vessel displacement versus time over a 24-hour period

of material in the hopper versus time for load 120, and Figure 27, which shows the vessel displacement versus time for that same load. Note that this is the same load presented previously in Figures 8 through 22, but Figure 26 shows the volume of material in the hopper at the start and end of the load and Figure 27 shows the vessel displacement. Using those values along with the densities of the water and in-place sediments as previously set forth, the bin measure production for load 120 is calculated as follows:

a. *Measured variables:*

V_S = 580 yd^3

V_E = 1,200 yd^3

D_S = 2,580 tons

D_E = 3,630 tons

ρ_i = 121.9 lb/ft^3

ρ_w = 63.7 lb/ft^3

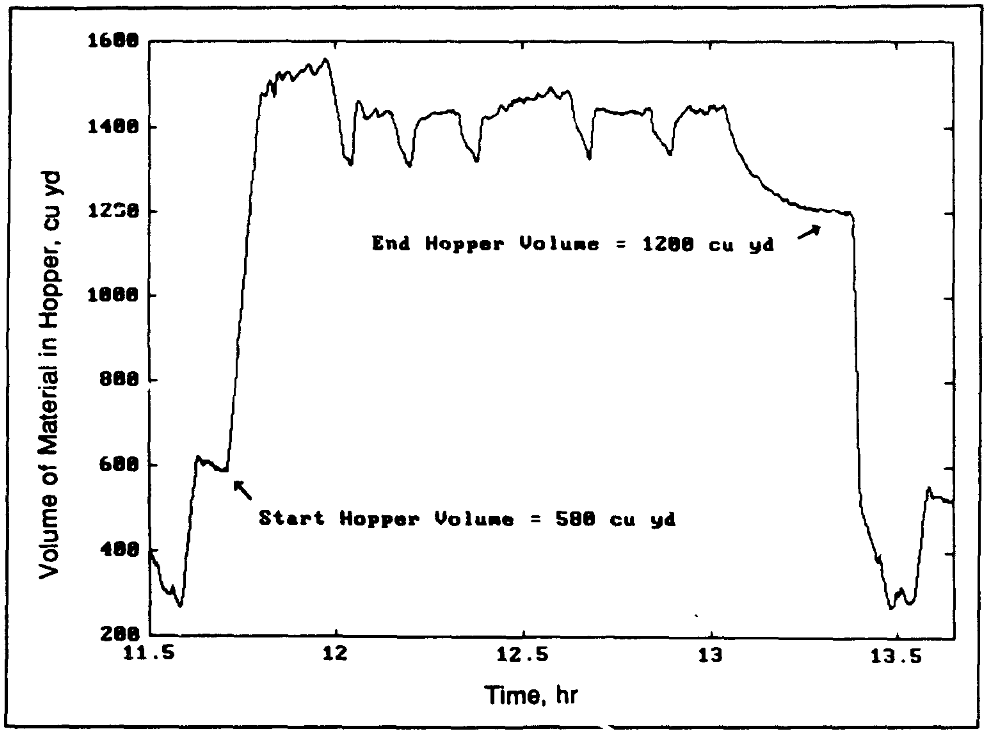

Figure 26. Volume of material in the hopper versus time for load 120, Chincoteague Inlet project

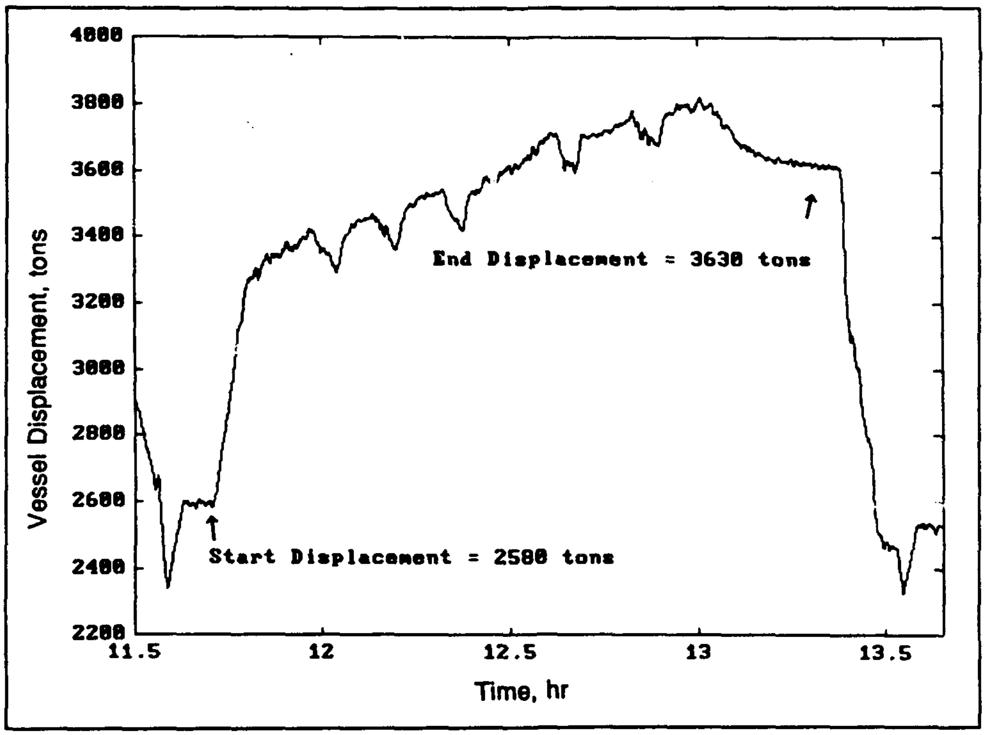

Figure 27. Vessel displacement versus time for load 120, Chincoteague Inlet project

b. Production calculations:

(1) *Bin water weight:*

$$\begin{aligned} BW &= V_S * \rho_w \\ &= (580\ yd^3 * 27\ ft^3/yd^3) * 63.7\ lb/ft^3 \\ &= 15{,}660\ ft^3 * 63.7\ lb/ft^3 \\ &= 997{,}542\ lb \end{aligned} \tag{10}$$

(2) *Total weight in hopper:*

$$\begin{aligned} TW &= (D_E - D_S) + BW \\ &= [(3{,}630 - 2{,}580)\ ton * 2{,}000\ lb/ton] + 997{,}542\ lb \\ &= (1{,}050\ tons * 2{,}000\ lb/ton) + 997{,}542\ lb \\ &= 2{,}100{,}000\ lb + 997{,}542\ lb \\ &= 3{,}097{,}542\ lb \end{aligned} \tag{11}$$

(3) Average density in hopper:

$$\begin{aligned} \rho_H &= TW / V_E \\ &= 3{,}097{,}542\ lb / (1{,}200\ yd^3 * 27\ ft^3/yd^3) \\ &= 3{,}097{,}542\ lb / 32{,}400\ ft^3 \\ &= 95.6\ lb/ft^3 \end{aligned} \tag{12}$$

(4) In-place production:

$$\begin{aligned} P_i &= [(\rho_H - \rho_w)/(\rho_i - \rho_w)] * V_E \\ &= [(95.6 - 63.7)/(121.9 - 63.7)] * 1{,}200\ yd^3 \\ &\quad (31.9/58.2) * 1{,}200\ yd^3) \\ &= 0.55 * 1{,}200\ yd^3 \\ &= 660\ yd^3 \end{aligned} \tag{13}$$

A total of 147 loads were dredged during the Chincoteague Inlet project. The procedure followed in the preceding example was used to calculate the bin measure production for each of those loads. The cumulative in-place bin measure production calculated was 84,110 yd^3 for an average load of 572.2 yd^3 over the 147 loads. Table A1 in Appendix A contains a complete listing of all loads for the Chincoteague Inlet project and includes load number, start and stop time from which each load was calculated, start and ending hopper volume and vessel displacement, the calculated bin water weight, calculated total weight in the hopper, average density in the hopper, and the in-place volume of material for each load. Those loads indicated by three asterisks (***) were water tests, which are discussed in the following section.

System verification-water tests

A potential weakness in this method of calculating production is the difficulty in verifying the accuracy of the data being measured. The total

displacement of the vessel and the volume of material in the hopper at any given time are difficult to verify. Thus, some method was needed to verify that the production calculations based upon the data collected by the monitoring system were accurate. No reasonable method of verifying each measurement could be determined, so a method of verifying the result of the average hopper density calculation was chosen. The water test method, adopted in this case, consisted of filling the hopper with a material of known density, and then calculating the average density of the material added to the hopper based upon the change in vessel displacement and volume of material added to the hopper as measured by the monitoring system. The hopper was filled with seawater, the density of which was determined from samples taken during the water tests. The vessel displacement and volume of material in the hopper were determined for the beginning and end of each water test. Figures 28 and 29 show the volume of material in the hopper and vessel displacement, respectively, for a water test. The values indicated in those figures for volume of material in the hopper and vessel displacement at the start and end of the test are used in the following calculations. Note that the same measured variables are used here as were used in the production calculation (Equations 10 through 13).

a. Weight added to hopper:

$$\begin{aligned} W_A &= D_E - D_S \\ &= (2{,}950 \text{ tons} - 2{,}270 \text{ tons}) * 2{,}000 \text{ lb/ton} \\ &= 1{,}360{,}000 \text{ lb} \end{aligned} \tag{14}$$

b. Volume added to hopper:

$$\begin{aligned} V_A &= V_E - V_S \\ &= (1{,}115 \text{ yd}^3 - 325 \text{ yd}^3) * 27 \text{ ft}^3/\text{yd}^3 \\ &= 21{,}330 \text{ ft}^3 \end{aligned} \tag{15}$$

c. Average sensity in hopper:

$$\begin{aligned} \rho_H &= W_A / V_A \\ &= 1{,}360{,}000 \text{ lb} / 21{,}330 \text{ ft}^3 \\ &= 63.8 \text{ lb/ft}^3 \end{aligned} \tag{16}$$

d. Measured density of water:

$$\rho_w = 63.7 \text{ lb/ft}^3 \tag{17}$$

e. Percent difference:

$$\begin{aligned} PD &= [(\rho_H - \rho_w) / \rho_w] * 100 \\ &= [(63.8 - 63.7) / 63.7] * 100 \\ &= 0.16 \text{ percent} \end{aligned} \tag{18}$$

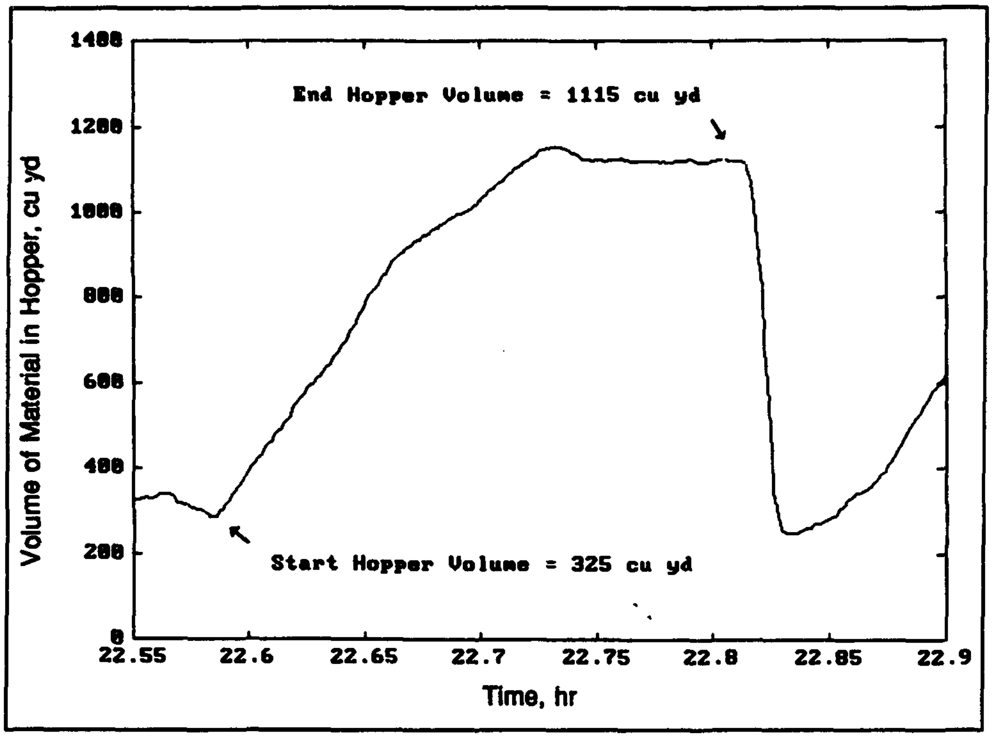

Figure 28. Volume of material in hopper versus time for water test, Chincoteague Inlet project

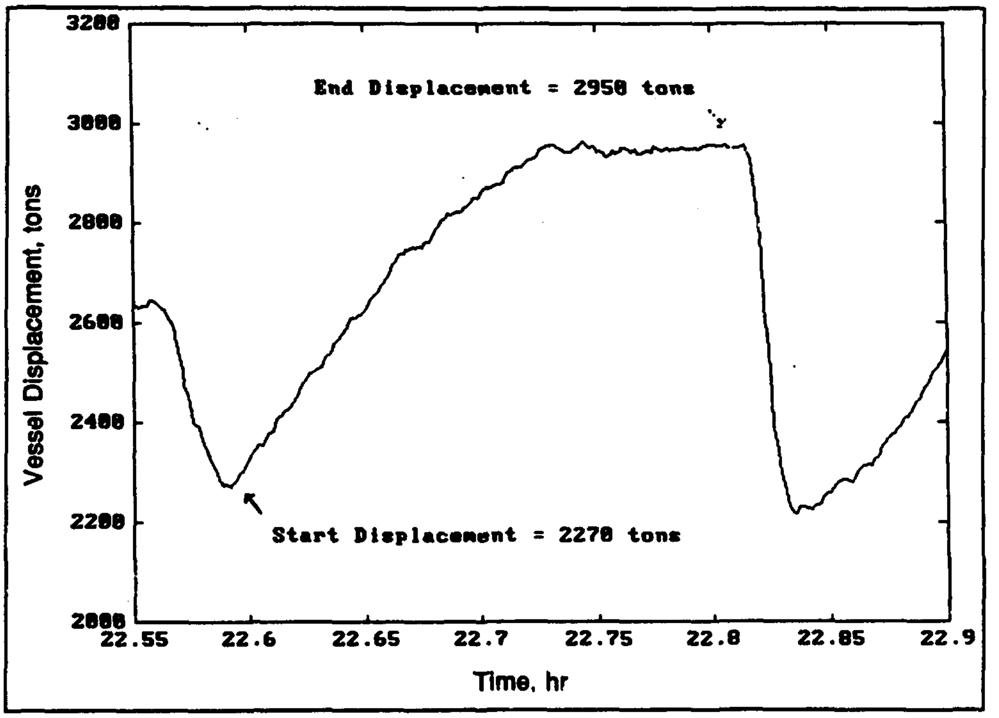

Figure 29. Vessel displacement versus time for water test, Chincoteague Inlet project

Water tests were conducted nearly every day of dredging on the Chincoteague Inlet project. The tests were typically performed after a load was dumped and the dredge was moving back to the dredging site. The data for these tests were gathered under the prevailing conditions at the dredging site. Therefore, the data should reflect the same degree of accuracy as the data gathered during the actual dredging. The results consistently showed that the calculated average density of the seawater in the hopper, was very close to the actual density of the water. A summary of those tests is presented in Table 2.

Table 2
Summary of Water Tests for Chincoteague Inlet

Date	Start Hopper Volume yd^3	End Hopper Volume yd^3	Start Displacement tons	End Displacement tons	Average Density in Hopper lb/ft^3
March 7	377	707	2,265	2,557	65.5
March 8	326	910	2,136	2,654	65.7
March 9	348	1,265	2,302	3,099	64.4
March 10	443	1,158	2,330	2,941	63.3
March 10	353	1,243	2,180	2,951	64.2
March 11	344	1,345	2,239	3,092	63.1
March 12	350	1,222	2,306	3,079	65.7
March 15	348	1,069	2,371	2,994	64.0
March 16	325	1,115	2,270	2,950	63.8
Average of Water Tests					64.4

As seen in Table 2, the average calculated density of the seawater added to the hopper during the nine water tests based upon the data acquired by the monitoring system was 64.4 lb/ft^3. The actual density of that water, as determined by analyzing water samples taken during five of the water tests, was 63.7 lb/ft^3. The percent difference between the density as determined by the monitoring system and the density as determined from the water samples is as follows.

a. Average density (monitoring system) = 64.4 lb/ft^3

b. Average density (water samples) = 63.7 lb/ft^3

c. Percent difference = [(64.4 - 63.7) / 63.7] * 100 = +1.1 percent

Several important factors can influence the final in-place production calculation, perhaps the most important and most uncertain of which is the in-place

density of the sediment. The very nature of the navigation channels where bin measure may be necessary, due to the difficulty of performing accurate surveys, often makes it difficult to obtain an accurate estimate of in-place density. If the in-place density is not correct, then the final calculated in-place production will obviously not reflect the actual amount of material removed from the bottom. One way to avoid this problem would be to measure only the weight of solids in the hopper, and not the in-place volume. This would make the system independent of soil type and remove this source of potential inaccuracies (Rokosch 1989).

Other data acquired

The data acquired from the production meters, draghead depth, and ship's position were not thoroughly analyzed for the Chincoteague Inlet project. These items were included to verify that the information could in fact be measured and recorded, but a complete review of the data was beyond the scope of this project. Included in Figures 12 through 19 were plots of these data for a typical load during the Chincoteague Inlet project. The data could be used for various purposes, such as verifying that a load was dumped in the proper location, estimating the depth of dredging from the draghead depth data, and calculating production by integrating the production meter density and velocity data over time. However, the specific scope of the effort reported herein was to determine the bin measure production, and this portion of the report is limited to that scope.

Uncertainty analysis

The uncertainty of dredge production calculations based on data from the instrumentation installed by the U.S. Army Engineer Waterways Experiment Station (WES) can be estimated using general uncertainty analysis calculations (Scott 1993). This technique accounts for the uncertainty contributed by each variable in the data reduction equation used to calculate production. The bin measure production for the *Northerly Island* was calculated by the following equation:

$$P_i = \frac{\frac{W_H}{V_H} - \rho_w}{\rho_i - \rho_w} * V_H \tag{19}$$

where

W_H = average slurry weight in hopper, lb
V_H = average full hopper volume, ft^3
ρ_w = interstitial water density lb/ft^3
ρ_i = in-place sediment density, in lb/ft^3

with the ratio W_H/V_H representing the average density in the hopper. After the uncertainty analysis method is applied to the production equation, it can be used to calculate the percentage uncertainty in dredge production. The final form of the production uncertainty equation is:

$$\frac{U_{P_i}}{P_i} = \left[\left[\frac{\rho_H}{\rho_H - \rho_w} * \frac{U_{W_H}}{W_H} \right]^2 + \left[\frac{U_{\rho_w}}{\rho_i - \rho_w} - \frac{U_{\rho_w}}{\rho_H - \rho_w} \right]^2 + \left[\frac{-U_{\rho_i}}{\rho_i - \rho_w} \right]^2 + \left[\frac{-\rho_w}{\rho_H - \rho_w} * \frac{U_{V_H}}{V_H} \right]^2 \right]^{1/2} \tag{20}$$

where

U_{ρ_i} = uncertainty in the in-place density measurement
U_{W_H} = uncertainty in the slurry weight measurement
U_{ρ_w} = uncertainty in the water density measurement
U_{V_H} = uncertainty in the hopper volume measurement

The production equation contains four variables that contribute some uncertainty to the final production calculation. The following describes each variable and the estimated potential uncertainty associated with it.

a. *Water density*. During the dredging at Chincoteague Inlet, nine water samples were taken between 8 March and 18 March 1993. The mean density measured was 1.020 g/cm^3, with a maximum of 1.021 g/cm^3 and a minimum of 1.019 g/cm^3. Therefore the uncertainty value for the water to be used in the calculation is ± 0.001 g/cm^3.

b. *In-place sediment density*. The contractor, NATCO, provided data describing in-place density measurements with a nuclear density probe. Two stations were sampled in the project area, one at station 401+50, range -15, and another at station 382+25, range 67. Three density readings were made at each station. For station 401+50, the average density was 1.946 g/cm^3, with a maximum of 1.957 g/cm^3 and a minimum of 1.939 g/cm^3. For station 382+25, the average density measured was 1.960 g/cm^3, with a maximum of 1.964 g/cm^3 and a minimum of 1.953 g/cm^3. The overall average for both stations was 1.953 g/cm^3 with an overall maximum of 1.964 g/cm^3 and overall minimum of 1.939 g/cm^3. Because of the limited amount of data from the two stations, a conservative determination of in-place sediment uncertainty will be considered based on the potential in-place density found in sand sediments. The in-place density of sandy sediments will generally be within the approximate range of 1.9 to 2.0 g/cm^3, depending on the degree of compaction and fine sediment content. Therefore, for this

application, the uncertainty of the in-place sediment density was approximately ± 0.05 g/cm^3.

c. *Average slurry density.* The average density of the slurry in the hopper was indirectly measured by two instrumented systems. The volume that the slurry occupies in the hopper was measured by acoustic transducers located above the hopper. The weight of the slurry in the hopper was measured by pressure transducers that measure the hydrostatic pressure change due to the draft of the dredge. The average density was calculated by the following equation:

$$\rho_H = W_H / V_H \tag{21}$$

The average slurry density for all of the Chincoteague Inlet hopper loads was 1.45 g/cm^3.

d. *Hopper volume.* The hopper volume measurement made with the acoustic transducers has some error potential associated with it. The average full hopper volume over the Chincoteague loads was 1,262 yd^3. The manufacturer's stated accuracy for the temperature compensated acoustic transducers is 0.2 percent of the measurement range under ideal conditions. Assuming an accuracy to within 0.5 percent of the measurement range for a field application and a measurement range of approximately 18 ft gives an uncertainty of 0.09 ft. The linear portion of the hopper has an ullage of about 118 yd^3 per ft; therefore, the volume uncertainty was approximately ± 10.62 yd^3.

e. *Slurry weight.* The weight of the slurry in the hopper is measured by pressure transducers, which measure the hydrostatic pressure change as the dredge drafts under the slurry load. The pressure data are converted to feet of water, which is used to calculate the dredge displacement as a function of draft. The difference between the final and initial dredge displacement during loading is the slurry load. The average slurry weight for the Chincoteague loads was 1,376 tons. Water test data indicated an uncertainty in the load measurement of approximately 1.090; therefore, the uncertainty of the average load was ± 13.76 long tons.

With the variable uncertainties defined, the uncertainty in the average production calculation can be calculated. Inserting the variable uncertainties into Equation 20 results in an average production uncertainty of ± 6.6 percent. With an average production of 582 yd^3 for the Chincoteague Inlet job, the average load production uncertainty is therefore 582 yd$^3 \pm 38$ yd^3. Table 3 lists the average variables and their uncertainties used in the analysis.

Table 3
Dredge Production Uncertainty Analysis Variables and Uncertainties

Variable	Average Value	Uncertainty U
Water density - ρ_w	1.02 g/cm^3	0.001 g/cm^3
In-place density - ρ_i	1.953 g/cm^3	0.05 g/cm^3
Slurry weight - W_H	1,376 tons	13.76 tons
Slurry density - ρ_H	1.45 g/cm^3	---------
Hopper volume - V_H	1,262.0 yd^3	10.62 yd^3

Norfolk Harbor Channel

The second dredging project monitored during this study was performed in the Norfolk Harbor channel, which extends from deep water in Hampton Roads into the Elizabeth River. The outbound channel to the coal piers at Lambert Point is maintained to a depth of 50 ft, while other portions of the channel are maintained to depths of 40 and 45 ft. Figure 30 shows a vicinity map of the Norfolk Harbor area, with the general location of this maintenance dredging project noted near the Craney Island Disposal Area. The Norfolk Harbor maintenance dredging is typically performed by a cutterhead dredge, but the low bidder chose to perform a portion of the project with a hopper dredge. The channel had not been dredged by a hopper dredge since 1986, when a Government dredge was used. A contract hopper dredge had never been used to perform the maintenance dredging in this portion of the channel.

Monitoring the maintenance dredging in Norfolk Harbor presented an opportunity to analyze the data acquired by the monitoring system in a dredging environment much different from that found in the Chincoteague Inlet project. The sediment in Norfolk Harbor is primarily fine-grained, as opposed to the sandy sediment in Chincoteague Inlet. The dredging depth in Norfolk Harbor was approximately 52 ft while that in Chincoteague Inlet was approximately 15 ft, and dredged material was discharged from the hopper by pumping into a confined disposal area at Craney Island whereas the Chincoteague Inlet project used an unconfined ocean site for dumping. Additionally, no restrictions exist on overflow of sediment from the hopper in Norfolk Harbor. For the Norfolk Harbor project, the data from the monitoring system were used to analyze the retention rate of solids in the hopper during the overflow period for each load.

The Norfolk Harbor dredging project commenced on 10 April 1993, and the project was performed in two phases. One acceptance section was completed by the NATCO dredge *Northerly Island* on 20 April 1993, while the remainder of the project was subcontracted and completed by cutterhead dredge. The section completed by the *Northerly Island* was on the east toe of the outbound channel, between center-line stations 138+00 and 196+00 for a

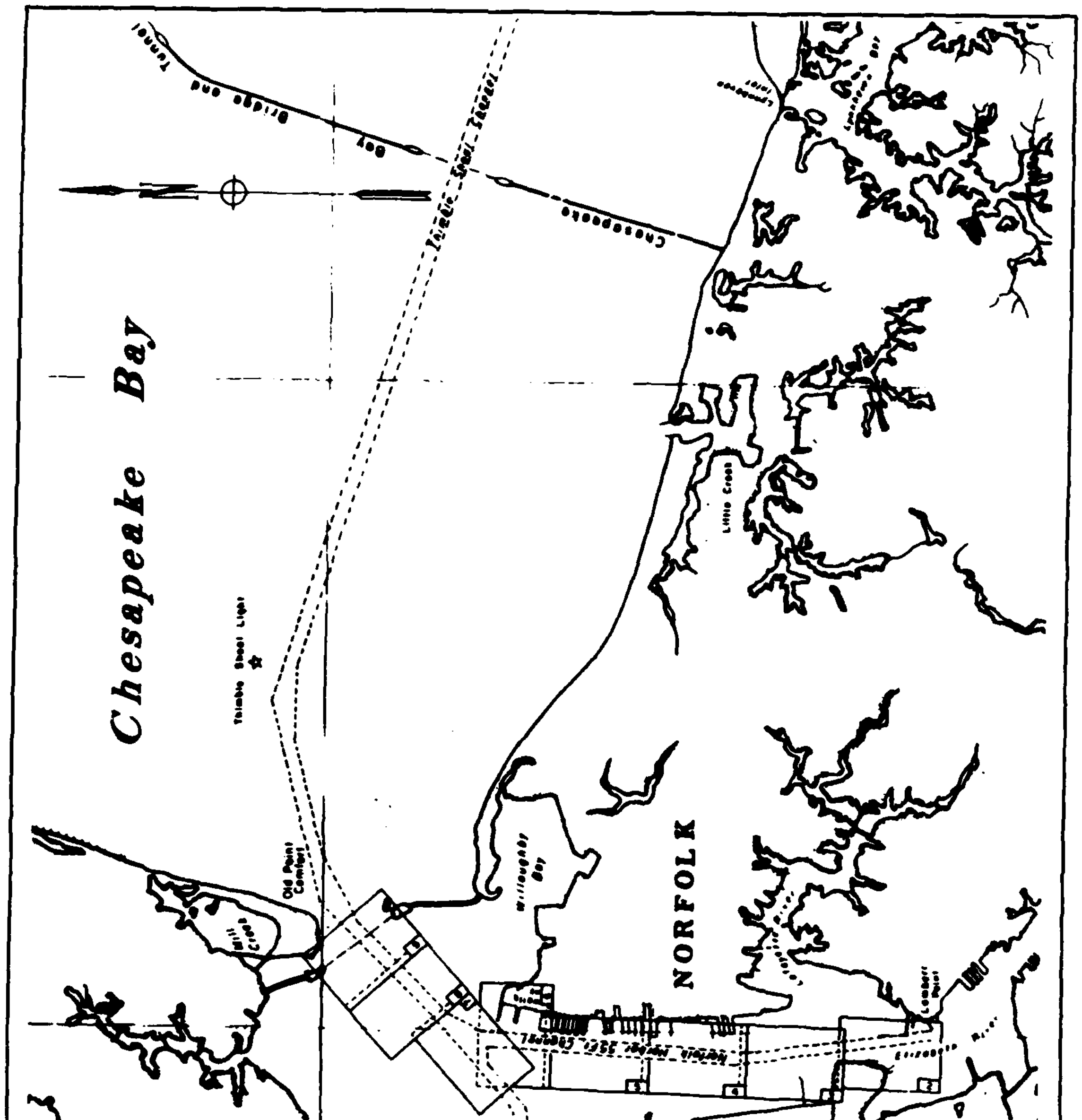

Figure 30. Vicinity map for Norfolk Harbor channel, Virginia

length of 5,800 ft. The data described in this report refer only to that portion of the project that was completed by the NATCO hopper dredge *Northerly Island*. The monitoring system installed by WES remained on the *Northerly Island* from the completion of the Chincoteague Inlet project in late March. The entire system was removed from the dredge on 21 April 1993, after *Northerly Island* had completed its work on the Norfolk Harbor project. The main goal of using the monitoring system on the Norfolk Harbor project was to analyze the amount of solids retained in the hopper during the overflow process. Monitoring the overflow efficiency using hopper volume, vessel displacement, and production meter data has previously been performed by WES aboard the U.S. Army Corps of Engineers dredge *Wheeler* (Scott 1992b).

Bin measure load calculations

Bin measure load calculations for the Norfolk Harbor project were performed in the same manner as for the Chincoteague Inlet project. However, unlike the Chincoteague Inlet project, payment for the Norfolk Harbor project was not based upon the in-place volume of material in the hopper, but upon the amount of material removed from the channel as determined from pre- and postdredging surveys. Note that the bin measure load calculations for this project do not provide a measure of the total amount of material removed from the channel, because the sediment lost during overflow is not retained in the hopper and is thus not reflected in the bin measure figures. Although the bin measure method does not reflect the total volume removed from the channel when overflow occurs, it does reflect that amount of material that remains in the hopper and is transported to the disposal site and may therefore provide an estimate of the volume of material added to the disposal area.

Table A2 in Appendix A is a summary of the bin measure load calculations for the loads monitored for the Norfolk Harbor Channel Project. A total of 90 loads were dredged by the *Northerly Island*, and the average calculated bin measure production was 734 yd^3 per load. Note that the data from midnight until approximately 2:30 p.m. on 17 April 1993 were missing from the data file for that day; thus the data for loads 66 through 70 are missing from Table A2.

Figures 31 and 32 show the volume of material in the hopper and the vessel displacement for load 74, a typical load from the Norfolk Harbor channel project. Using the values indicated in those figures for hopper volume and vessel displacement, the bin measure load is calculated using the same process as set forth previously. Note the difference between Figures 31 and 32 and Figures 26 and 27, which show the same type of data for a load from the Chincoteague Inlet project. Once the hopper was full and overflow began in the Norfolk Harbor project, the vessel displacement did not increase significantly, whereas the vessel displacement continued to increase during overflow in the Chincoteague Inlet project. This reflects the fact that very little of the Norfolk Harbor fine-grained sediments was being retained in the

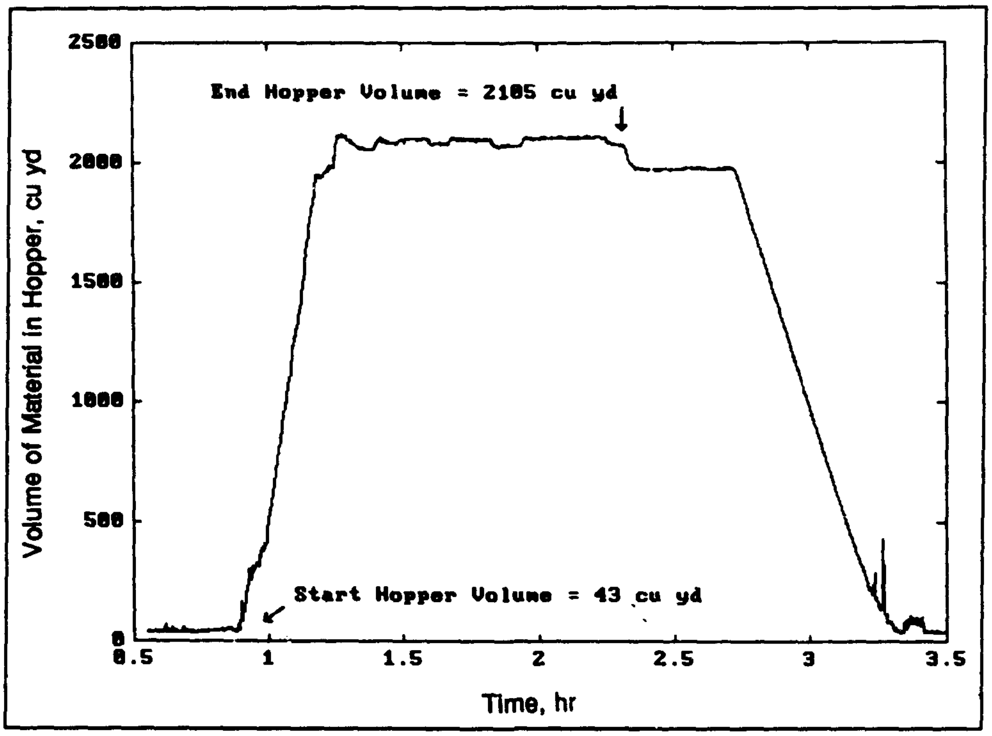

Figure 31. Volume of material in hopper versus time for load 74, Norfolk Harbor project

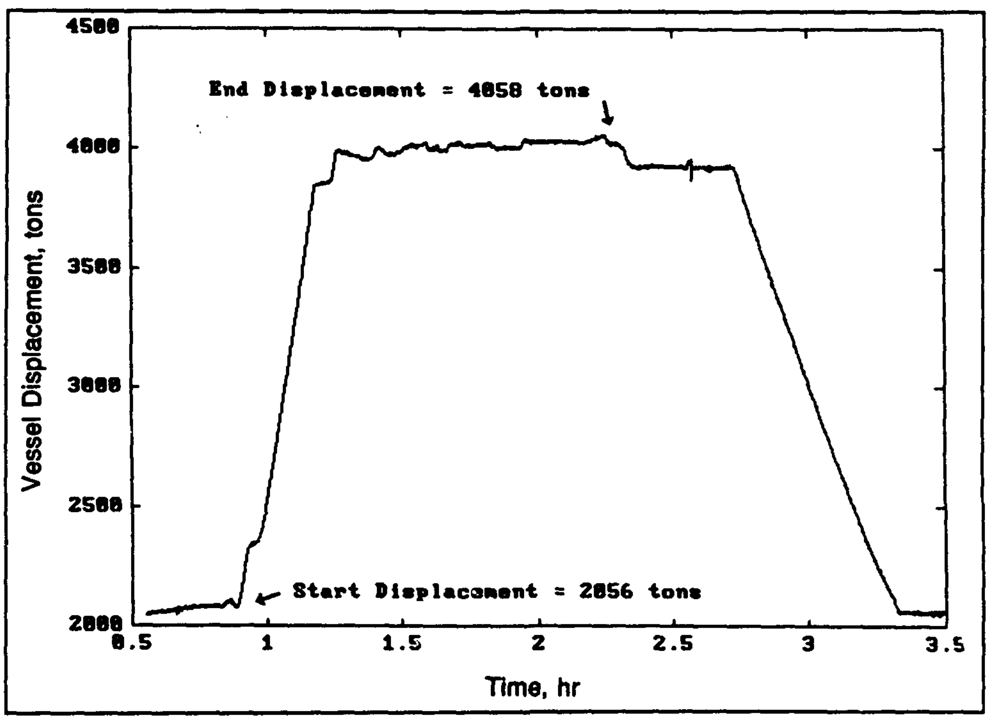

Figure 32. Vessel displacement versus time for load 74, Norfolk Harbor project

hopper while greater retention was achieved with the sandy sediments in Chincoteague Inlet. A more detailed analysis of the retention of sediments in the hopper during the Norfolk Harbor Channel project is presented later in this report.

System verification - water tests

Water tests were performed during the Norfolk Harbor project in the same manner as previously discussed for the Chincoteague Inlet project, and calculation of the water density was also performed as outlined for the Chincoteague Inlet project. Water tests were conducted on four occasions throughout the Norfolk Harbor project, the results of which are summarized in Table 4.

Table 4
Summary of Water Test Results for Norfolk Harbor Project

Date	Start Hopper Volume yd^3	End Hopper Volume yd^3	Start Displacement tons	End Displacement tons	Average Density in Hopper lb/ft^3
April 12	43	1,505	1,970	3,224	63.5
April 13	44	760	2,089	2,705	63.7
April 16	43	765	1,997	2,619	63.8
April 19	43	955	2,099	2,880	63.4
Average of Water Tests					63.6

From Table 4, the average density of seawater added to the hopper during the water tests, calculated from data acquired by the monitoring system, was 63.6 lb/ft^3. The actual water density, from water samples taken during the tests, was 62.8 lb/ft^3, the percent difference between the calculated and actual density being +1.3 percent.

Overflow analysis

The primary focus of monitoring the Norfolk Harbor channel project was to obtain some insight into the amount of solids retained in the hopper during overflow. Overflow is that portion of the dredging cycle that starts when the hopper is full and material is allowed to overflow back into the channel as dredging continues. When coarse-grained sediments are dredged, the solids will settle into the hopper while the overflow consists of relatively clear water. However, when the dredged material consists of fine-grained sediments, which take considerably longer to settle, the effectiveness of overflow in retaining solids in the hopper is less certain.

The beginning and ending of the overflow process for each load were determined from the hopper volume data. Overflow started when the hopper volume reached a maximum, and a relatively constant hopper volume was maintained while dredging continued. Overflow stopped when the production meters indicated that dredging had stopped for each load. Figure 33 shows a plot of vessel displacement and volume of material in the hopper for load 74, a typical load from the Norfolk Harbor project. Noted in that figure are the start and stop times of the overflow process for that particular load.

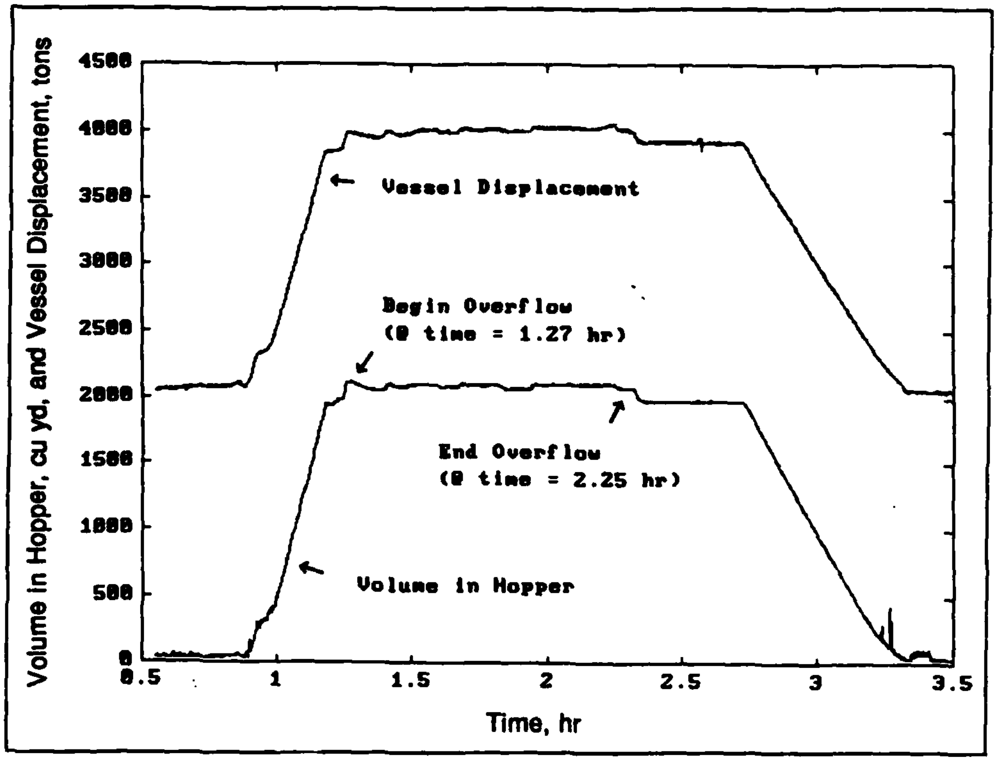

Figure 33. Volume of material in hopper and vessel displacement versus time for overflow analysis on load 74, Norfolk Harbor project

The amount of solids retained in the hopper was determined by comparing the total displacement, or weight, of the vessel at the start of overflow and the total weight at the end of overflow. Since the total volume of material in the hopper does not increase during overflow, any increase in the weight of the vessel during overflow must be due to additional solids displacing water and being retained in the hopper. Thus, the weight of solids retained during overflow was taken as the change in the total weight of the vessel during overflow, as determined from the monitoring system displacement measurements. Figure 34 is a magnified view of the vessel displacement during overflow for load 74, with the displacement of the vessel at the start and end of overflow noted. For the values indicated in Figure 34, the weight of solids retained in the hopper was calculated as follows:

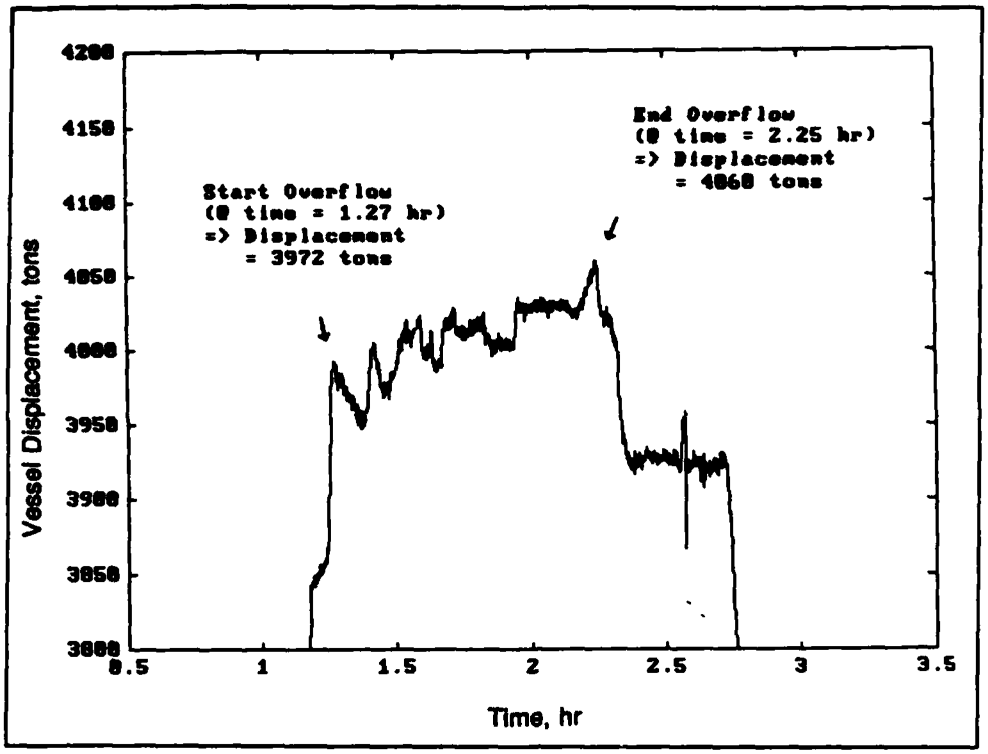

Figure 34. Vessel displacement versus time during overflow on load 74, Norfolk Harbor project

a. Weight of vessel at start of overflow = 3,972 tons

b. Weight of vessel at end of overflow = 4,060 tons

c. Weight of solids retained during overflow = 88 tons

To determine the percentage of solids retained in the hopper during overflow, the total weight of solids pumped into the hopper during overflow must be known. That value was determined from the production meter data. As outlined in Chapter 2 of this report, the density and velocity of dredged material in each drag arm were used to calculate the cumulative weight of solids pumped. The total weight of solids pumped during overflow for each load was taken as the cumulative weight of solids pumped from the start of overflow through the end of overflow, as calculated from the production meter data. Figure 35 shows the cumulative weight of solids pumped during load 74, the same load depicted in Figures 33 and 34. Note that the time scale in Figure 35 has been adjusted such that the plot covers only that portion of the load when overflow was occurring (from 1.27 hr to 2.25 hr). The cumulative weight of solids pumped during overflow for that load, shown in Figure 35, represents the total weight of solids available for retention in the hopper during overflow. The weight of solids retained divided by the weight of solids

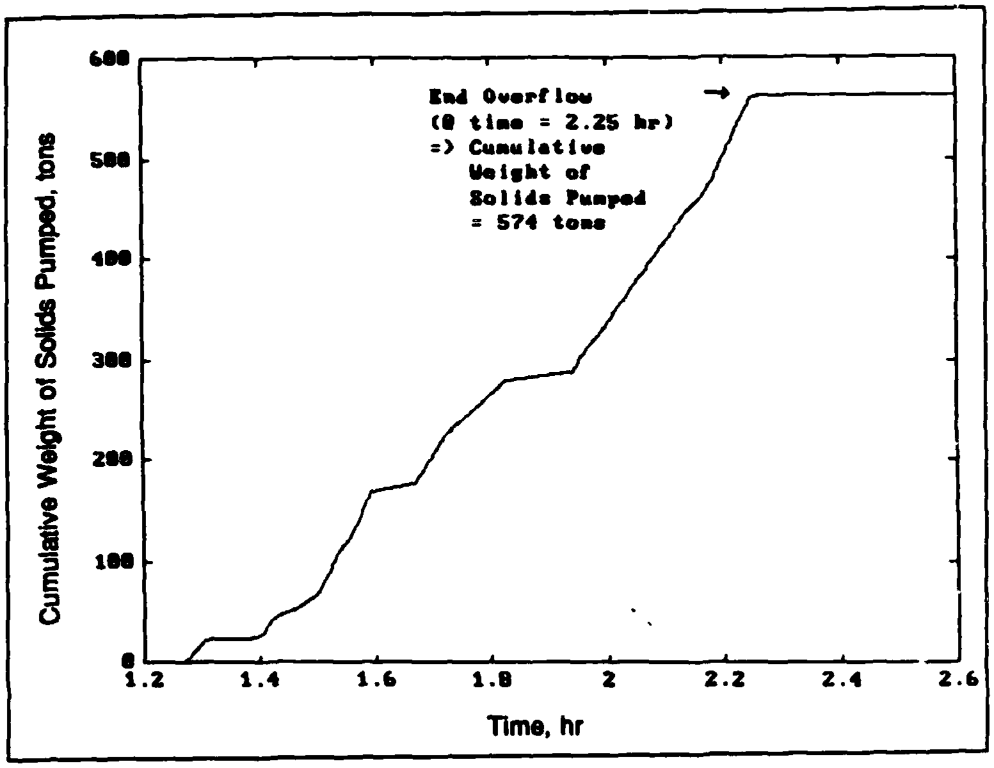

Figure 35. Cumulative weight of solids pumped versus time during overflow on load 74, Norfolk Harbor project

available provided the percentage of solids retained during overflow as follows:

a. Weight of solids retained = 88 tons

b. Weight of solids available = 574 tons

c. Percentage of solids retained = (87 / 574) * 100 = 15.3 percent

Table A3 in Appendix A summarizes the overflow analysis for the entire portion of the project that was monitored. As seen in that table, the average percent of solids retained throughout the project was 15.5 percent, so that during overflow an average of 84.5 percent of the solids pumped into the hopper were returned directly overboard back into the channel.

Other data acquired

The data acquired for the draghead depth and ship's position were not analyzed for the Norfolk Harbor channel project. As with the Chincoteague Inlet project, the intent of including those items in the monitoring system was to verify that the information could in fact be measured and recorded, but a complete review of those was beyond the scope of this study. The specific

scope of the effort for monitoring the Norfolk Harbor channel project was to analyze the amount of overflow retained in the hopper during overflow, as discussed in the preceding section.

Uncertainty analysis

The uncertainty of dredge production calculations based on data from the dredge *Northerly Island* production meters can also be approximated using the general uncertainty analysis technique. The solids mass production through the *Northerly Island* production meters was calculated using Equation 8.

After the uncertainty analysis method is applied to the solids mass production equation, it can be used to calculate the percentage uncertainty. The final form of the production uncertainty equation is:

$$\frac{U_{M_s}}{M_s} = \left[\left(\frac{U_{\rho_m}}{\rho_m - \rho_w} \right)^2 + \left(\frac{U_{\rho_s}}{\rho_s} - \frac{U_{\rho_s}}{\rho_s - \rho_w} \right)^2 + \left(\frac{U_{\rho_w}}{\rho_s - \rho_w} - \frac{U_{\rho_w}}{\rho_m - \rho_w} \right)^2 + \left(\frac{U_{V_m}}{V_m} \right)^2 + \left(\frac{2U_{D_p}}{D_p} \right)^2 \right]^{1/2} \tag{23}$$

where,

D = pipe diameter (in.)
U_{M_S} = uncertainty in the solids mass production measurement
U_{ρ_m} = uncertainty in the slurry density measurement
U_{ρ_s} = uncertainty in the sediment particle density measurement
U_{V_m} = uncertainty in the slurry velocity measurement
U_{Dp} = uncertainty in the pipeline diameter

The solids mass production equation contains the following five variables that contribute some uncertainty into the final production calculation.

a. *Water density*. Four water samples were taken during the Norfolk Harbor project. Laboratory analysis of each of the samples indicated a water density of 1.007 g/cm^3. Although each sample had the same measured density, an uncertainty value of ± 0.001 g/cm^3 will be used for this analysis.

b. *Sediment particle density*. The sediments found in the Norfolk Harbor area consisted mainly of silt, with an approximate in-place density of 1.45 g/cm^3. To determine the uncertainty in the particle density of the Norfolk Harbor sediments, test data were obtained from a soil survey of Norfolk Harbor (Swean 1986). Test data for nine samples were evaluated. The average particle density for the nine samples

was 2.65 g/cm^3, with a minimum of 2.57 g/cm^3 and a maximum of 2.73 g/cm^3. This indicates an approximate density range of 3.0 percent; therefore the particle density uncertainty is 2.65 g/cm^3, $\pm$0.079 g/cm^3.

c. *Slurry density.* The density meter used to measure slurry density is considered very accurate when used with homogeneous liquids. The accuracy rating from the manufacturer in measuring density is $\pm$0.001 g/cm^3. For dredging applications with mixed sediment slurries existing within varying phases of flow, the accuracy is potentially somewhat less. An estimate of the accuracy of density gauges used in dredging applications is $\pm$0.005 g/cm^3. The average density of the slurry pumped during the Norfolk job was approximately 1.10 g/cm^3. Therefore the slurry density uncertainty is 1.10 g/cm^3 $\pm$0.005 g/cm^3.

d. *Slurry velocity.* The slurry velocity was measured using a magnetic flowmeter. These meters are considered the most accurate method for determining slurry velocities for dredging applications. The manufacturer's stated accuracy for a properly calibrated flowmeter is $\pm$0.25 percent of full scale. For the purpose of this uncertainty calculation, a conservative accuracy of $\pm$1.0 percent of full scale was used. The full scale of the magnetic flowmeter was 32.80 ft/sec, and the average pumping velocity during the Norfolk Harbor project was approximately 13.0 ft/sec. Therefore, the uncertainty in the average velocity measurement was 13.0 ft/sec $\pm$0.33 ft/sec.

e. *Pipeline diameter.* There is some assumed error in the measurement of the diameter of the discharge pipe on a dredge, as well as uncertainty due to eccentricity of the pipe. Because many makes of pipe are used in dredging, an assumed uncertainty of 0.05 in. will be used for the following error analysis.

With the variable uncertainties defined, the uncertainty in the average calculation of solids mass production can be calculated. Inserting the variable uncertainties into Equation 23 results in an average uncertainty of $\pm$6.0 percent. Table 5 lists the average variables and their uncertainties used in the analysis.

Table 5
Dredge Production Uncertainty Analysis Variables and Uncertainties

Variable	Average Value	Uncertainty U
Water density ρ_w	1.007 g/cm^3	0.001 g/cm^3
Particle density ρ_s	2.65 g/cm^3	0.079 g/cm^3
Slurry density ρ_m	1.100 g/cm^3	0.005 g/cm^3
Slurry velocity V_m	13.0 ft/sec	0.33 ft/sec
Pipe diameter D	18.0 in.	0.05 in.

4 Summary and Conclusions

System Reliability and Accuracy

The automated dredge monitoring system provided accurate and reliable data throughout both the Chincoteague Inlet and Norfolk Harbor projects. The water test data confirmed the accuracy and reliability of the data, and the uncertainty analyses revealed an average production uncertainty of ± 6.2 percent for the bin measure production calculation and an average uncertainty of ± 6.0 percent for the solids mass production calculation. The major potential limitation to the accuracy of the bin measure production calculation is accurate measurement of in-place sediment and water densities. After the initial installation of the system, no additional maintenance or calibration was performed during the 2 months that it was in place, so the system was reliable through the course of this study. Therefore, the monitoring system does in fact provide an accurate, simple, and reliable method of monitoring the dredge's performance.

Uses for the System

As detailed in this report, producing data for bin measure production calculations and overflow analysis are two potential uses for the monitoring system. For bin measure calculations, the volume of in-place sediment in the hopper can be determined for each load, assuming that an accurate measurement of the in-place sediment density is available. For overflow operations, the exact point in time when overflow starts and stops can easily be determined; and if production meter data are being recorded, then the amount of material that is overflowed can be calculated. Thus, if overflow is not allowed on a project, or if overflow is allowed only for a specified time, compliance with those overflow parameters can be monitored and verified 24 hours per day.

Another potential use is for monitoring disposal operations. If dumping in a specific location is critical, then the exact location where each dump occurs can be determined if the ship's position is recorded. Therefore, dumping short of the dump site or dumping out of the authorized dump area can be

monitored, which may be particularly critical if contaminated sediments are involved.

System Weaknesses

Two potential weaknesses of the system need to be addressed. One is that the large volumes of data recorded require sufficient storage space. Recording data every 5 seconds during the 24 hours of a day results in 17,280 data points for each channel of data. For this project, 10 channels of data were recorded, with the resulting data file for each 24-hour day stored in binary format requiring 933,120 bytes of storage space. The amount of data collected and the available space on the hard drive on this project allowed for data to be collected every 5 seconds, 24 hours per day for 63 days before the disk was full. If a project continues for any length of time, the volume of data can quickly become difficult to store and manage. The feasibility of recording data less frequently than 5-second intervals could be considered to alleviate this problem.

The other potential weakness of the monitoring system involves analysis of the data. Plotting the data to analyze each load to calculate the bin measure production or overflow efficiency requires the proper computer hardware and software. A very tedious process is required if the calculations are not automated in some manner. Thus, a menu-driven computer program should be developed that would provide plots of the data, perform production calculations, allow for overflow analysis, and generate reports. Such a program would enable the onsite engineer or inspector to easily retrieve the data from the monitoring system, analyze the data as necessary, and produce pertinent and useful information relative to the dredging project.

System Benefits

The benefits of installing an automated load monitoring system during a dredging project are many. The ease, accuracy, and reliability with which bin measure production, overflow, dredge location, and other dredge processes can be monitored is a vast improvement over the methods typically used. The ability to store data electronically for future use is also extremely helpful, particularly if that information is needed in planning future projects or in dealing with litigation that may arise from a dredging contract.

The focus to this point has been primarily on benefits to the Government. There are, however, benefits to the contractor. The data gathered by this system could be used by the contractor to analyze the performance of the dredge and the crew during a project. Changes in operating procedures aboard the dredge to improve efficiency could result. This load monitoring system also eliminates the need for the contractor to perform a daily "lightship" test with the hopper dredge. Currently, a contractor often performs

light-ship tests during which the hopper is filled with water to determine the total displacement of the ship with only water in the hopper. When dredging resumes, the weight of dredged material in the hopper is determined by comparing the total displacement of the ship when the hopper is full of dredged material with the total displacement of the ship from the light-ship test. These tests are often performed daily so that variations due to changes in the weight of fuel, water, and other consumables aboard the ship can be accounted for. With the implementation of an automated system, the need for the light-ship test will be eliminated because the change in the weight of fuel, water, and other consumables aboard the ship is almost always negligible during the time required for one load cycle. Thus, the time and fuel previously required for the light-ship tests could then be used by the contractor for productive dredging.

Conclusions

When payment to the contractor in a dredging contract is to be based upon measurement of the weight of the dredged material in the hopper as determined by vessel displacement, or "bin measure," it is imperative that a system be developed that will allow simple, reliable, and unbiased verification of the load measurements reported by the contractor (McDonnell and Tillman 1992). Additionally, monitoring of the overflow process is becoming increasingly important as environmental concerns are addressed, and a system for automatically monitoring overflow is also critical.

A system that automatically monitored both the bin measure production and the overflow process was designed and successfully field tested during this project. Implementation of such a system for actual payment purposes is very feasible. However, before payment to the contractor is made based solely upon the information gathered by this system, additional evaluation of the accuracy is recommended. This recommendation is based upon the possibility of disputes arising over the production indicated by the monitoring system and in the resulting need to be able to defend the accuracy of the system in a court of law. Additionally, development of software to enable both the Government and the contractor to more easily use the data collected by the system is necessary. No matter how good the information may be from the load monitoring system, it is of very little use if it cannot be analyzed relatively easily by engineers in field offices. If the proper research and development is dedicated to the automated dredge monitoring concept, then the result should be a system in which both the Government and the contractor have trust and confidence that an accurate and unbiased record of the dredge's performance is being provided. This system can provide information that will be beneficial to both the Corps of Engineers and the dredging industry.

References

Consolidated Electrodynamics Corporation. (1956). "Type 4-312 pressure pickup, technical specifications," Pasadena, CA.

Lundahl Instruments, Inc. (1991). "DCU-10 programmable ultrasonic sensor, operator's manual," Logan, UT.

McDonnell, Thomas M., and Tillman, Russell K. (1992). *"Dredge Data-Logging System:* a prelude to the Silent Inspector," Dredging Research Program Information Exchange Bulletin, Vol DRP-92-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, 1-5.

Rokosch, W. Dieter. (1989). "Measuring dry matter in trailing hopper dredges." *Dredging technology, environmental, mining*; proceedings of WODCON XII, Orlando, FL, May 2-5, 1989. World Dredging Mining and Construction, Irvine, CA, 13-20.

Scott, Stephen H. (1992a). "Applying ultrasonic surface detectors to hopper dredge production monitoring," Dredging Research Technical Notes, Vol DRP-3-06, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

__________. (1992b). "Improving hopper dredge overflow operations with production monitoring technology," Dredging Research Program Information Exchange Bulletin, Vol DRP-92-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, 1-5.

__________. (1993). "An Uncertainty Analysis of Dredge Production Measurements and Calculations," *Journal of Waterway, Port, Coastal and Ocean Engineering,* ASCE, 119(2), 193-203.

Swean, W. Jerry. (1986). "Geology and soils subsurface investigation, Norfolk Harbor Channel, Norfolk Harbor and Channels, Virginia," Appendix C, Vol 1, U.S. Army Engineer District, Norfolk, Norfolk, VA.

U.S. Army Corps of Engineers. (1985). "Hopper dredge operating characteristics," U.S. Army Corps of Engineers Water Resources Support Center, Fort Belvoir, VA.

Appendix A
Bin Measure Load Data and Overflow Analysis Data

Table A1
Summary of Bin Measure Load Data, Chincoteague Inlet Project

Load Number	Start Time hr	End Time hr	Hopper Volume, yd^3 Starting	Hopper Volume, yd^3 Ending	Displacement, tons Starting	Displacement, tons Ending	Bin Water Weight lb	Total Weight in Hopper lb	Average Density in Hopper lb/ft^3	In-Place Production yd^3
1	7.499	8.124	1068	1242	2788	3236	1835515	2732525	81.4	379
2	8.435	9.236	767	1260	2555	3301	1319450	2811014	82.6	410
3	9.506	10.476	1050	1322	2816	3345	1805364	2861575	80.1	374
4	10.778	11.761	774	1232	2570	3268	1330685	2727561	82.0	387
5	12.106	13.051	518	1181	2378	3347	890260	2827300	88.6	506
6	13.407	14.303	718	1260	2537	3546	1235314	3252722	95.6	691
7	14.707	15.824	711	1301	2531	3713	1222860	3587056	102.1	859
8	16.222	17.326	558	1329	2408	3793	959441	3729352	103.9	919
9	17.640	18.982	576	1365	2432	3809	990649	3744230	101.6	889
10	19.246	20.736	783	1174	2611	3656	1346310	3435530	108.4	901
11	21.012	21.949	820	1222	2639	3373	1410249	2877681	87.2	493
12	22.208	23.147	927	1213	2718	3314	1593718	2784414	85.0	444
13	23.637	0.896	902	916	2732	3159	1550083	2404083	97.2	528
14	1.365	2.107	795	1213	2609	3268	1366526	2684326	81.9	381
15	2.482	3.535	618	1250	2477	3621	1062066	3349280	99.2	763
16	3.858	4.937	492	1276	2389	3640	847145	3349534	97.2	735
17	5.301	6.490	646	1465	2513	3825	1111336	3734272	94.4	773

(Sheet 1 of 10)

Table A1 (Continued)

Load Number	Start Time hr	End Time hr	Hopper Volume, yd^3		Displacement, tons		Bin Water Weight lb	Total Weight in Hopper lb	Average Density in Hopper lb/ft^3	In-Place Production yd^3
			Starting	Ending	Starting	Ending				
18	6.787	8.583	579	1344	2455	4060	995749	4204911	115.8	1204
19	9.319	10.356	524	1296	2438	3579	901333	3183522	90.9	607
20	10.683	11.426	751	1260	2611	3316	1290700	2701531	79.4	340
21	12.029	12.501	645	1202	2495	3166	1108471	2451450	75.5	244
22	12.906	13.551	563	1181	2407	3194	967548	2542813	79.7	325
23	13.878	14.901	289	1219	2226	3520	496947	3084834	93.7	629
24	15.328	16.203	588	1245	2439	3492	1011901	3117118	92.7	620
25	16.606	17.679	618	1267	2471	3620	1062391	3360535	98.2	751
***	17.840	18.029	377	707	2265	2557	---	---	64.5	---
26	18.196	20.067	847	1319	2699	3999	1456248	4055618	113.9	1137
27	20.442	22.075	278	1342	2168	3485	478830	3113452	85.9	512
28	22.654	23.511	272	1262	2122	3192	468957	2608451	76.5	279
29	0.062	0.451	775	1224	2568	3118	1332961	2432722	73.6	209
30	0.860	1.554	684	1188	2422	3062	1175987	2455977	76.5	262
31	2.064	2.756	635	1191	2381	3134	1092461	2596926	80.7	349
32	3.053	4.015	567	1218	2330	3320	975736	2954645	89.8	547

(Sheet 2 of 10)

*** = Water Test

Table A1 (Continued)

Load Number	Start Time hr	End Time hr	Hopper Volume, yd^3		Displacement, tons		Bin Water Weight lb	Total Weight in Hopper lb	Average Density in Hopper lb/ft^3	In-Place Production yd^3
			Starting	Ending	Starting	Ending				
33	4.372	5.414	614	1268	2379	3402	1056417	3101917	90.6	586
34	5.707	8.051	621	1333	2380	4010	1068892	4329289	120.2	1295
***	8.444	8.694	326	910	2136	2654	---	---	64.9	---
35	8.721	11.226	263	1148	2093	3138	453425	2543740	82.0	362
36	11.726	12.392	601	1251	2363	3060	1034434	2429141	71.9	176
37	12.710	13.371	621	1205	2355	3055	1068120	2467426	75.8	252
38	13.714	14.385	529	1339	2269	3201	909236	2774266	76.7	300
39	14.712	15.365	451	1396	2309	3284	775144	2725020	72.3	206
40	15.654	16.504	654	1221	2398	3249	1124136	2825345	85.7	462
41	16.836	17.842	852	1245	2565	3425	1465371	3184656	94.7	664
42	18.278	19.861	964	1261	2703	3732	1657931	3715874	109.1	984
43	20.282	22.635	291	1211	2110	3722	500878	3724499	113.8	1044
44	23.203	0.308	393	1182	2204	3204	676141	2676141	83.9	411
45	0.940	1.451	432	1179	2248	3074	742600	2394303	75.2	234
46	1.926	2.642	562	1225	2339	3199	966268	2687583	81.2	369
47	3.104	3.806	618	1195	2381	3061	1062919	2422862	75.0	234

(Sheet 3 of 10)

*** = Water Test

Table A1 (Continued)

Load Number	Start Time hr	End Time hr	Hopper Volume, yd³ Starting	Hopper Volume, yd³ Ending	Displacement, tons Starting	Displacement, tons Ending	Bin Water Weight lb	Total Weight in Hopper lb	Average Density in Hopper lb/ft³	In-Place Production yd³
48	4.365	5.514	620	1250	2408	3538	1067023	3326001	98.5	749
49	5.914	8.229	384	1343	2223	4133	661081	4480580	123.6	1382
50	8.862	10.529	389	1284	2251	3630	668737	3427224	98.8	775
51	11.154	12.224	618	1185	2468	3352	1063203	2831064	88.4	504
52	12.754	13.101	595	1258	2413	3178	1023970	2553519	75.1	248
53	13.782	14.201	843	1201	2640	3106	1448914	2381765	73.4	201
54	14.701	15.351	757	1184	2530	3105	1302606	2452399	76.7	264
55	15.718	16.504	998	1187	2723	3261	1715560	2790654	87.1	477
56	16.843	18.001	652	1158	2477	3350	1121434	2868151	91.7	558
***	18.146	18.469	348	1265	2302	3099	---	---	64.2	---
57	18.358	19.790	306	1410	2236	3795	526427	3644359	95.7	776
58	20.408	22.068	1006	1335	2794	3728	1729457	3596887	99.8	828
59	22.407	0.108	709	1208	2544	3447	1219588	3025588	92.8	605
60	0.439	1.401	602	1206	2448	3486	1035775	3112099	95.5	660
61	1.826	2.440	634	1360	2468	3252	1090510	2658268	72.4	204
62	3.049	3.603	466	1202	2324	3184	800831	2521614	77.7	289

(Sheet 4 of 10)

*** = Water Test

Table A1 (Continued)

Load Number	Start Time hr	End Time hr	Hopper Volume, yd³ Starting	Hopper Volume, yd³ Ending	Displacement, tons Starting	Displacement, tons Ending	Bin Water Weight lb	Total Weight in Hopper lb	Average Density in Hopper lb/ft³	In-Place Production yd³
63	4.019	4.600	696	1234	2516	3262	1197280	2690291	80.7	362
64	4.958	5.753	565	1216	2428	3294	972099	2703345	82.3	389
65	6.143	8.061	654	1360	2515	4205	1124725	4505722	122.7	1378
66	8.654	9.610	441	1287	2353	3602	758090	3255702	93.6	663
67	10.131	11.124	895	1257	2691	3528	1538779	3211139	94.6	668
***	11.365	11.551	443	1158	2330	2941	---	---	63.4	---
68	11.585	12.404	263	1238	2157	3445	452089	3026556	90.5	571
69	12.853	13.667	423	1281	2277	3382	728617	2937772	84.9	468
***	13.771	14.172	353	1243	2180	2951	---	---	64.0	---
70	14.411	14.910	329	1212	2155	3142	566764	2539063	77.5	289
71	15.433	15.861	525	1215	2314	3031	903344	2338656	71.3	159
72	16.401	17.508	619	1239	2363	3392	1064260	3122069	93.3	631
73	17.814	19.481	306	1432	2079	3582	526246	3530664	91.3	680
74	19.714	21.436	365	1418	2097	3607	627969	3647190	95.3	769
75	21.624	23.551	347	1456	2114	3840	597827	4050103	103.0	983
76	0.011	1.210	556	1414	2313	3570	956028	3469093	90.9	660

(Sheet 5 of 10)

*** = Water Test

Table A1 (Continued)

Load Number	Start Time hr	End Time hr	Hopper Volume, yd³		Displacement, tons		Bin Water Weight lb	Total Weight in Hopper lb	Average Density in Hopper lb/ft³	In-Place Production yd³
			Starting	Ending	Starting	Ending				
77	1.533	2.414	965	1404	2636	3531	1659117	3449032	90.9	658
78	2.639	5.806	345	1263	2114	3106	593328	2577717	75.6	258
79	6.325	7.851	350	1272	2148	3504	602912	3314251	96.5	717
80	8.610	10.103	537	1279	2329	3735	924332	3736504	108.1	977
81	10.635	11.772	391	1322	2234	3456	672498	3116077	87.3	536
82	12.297	13.836	997	1240	2727	3608	1713894	3476639	103.8	855
83	14.203	15.014	661	1188	2481	3301	1137322	2775661	86.5	466
84	15.603	15.964	902	1315	2660	3199	1550197	2628705	74.0	233
85	16.874	17.211	1001	1398	2758	3267	1720334	2738486	72.5	213
86	17.792	18.471	949	1351	2717	3362	1631387	2920997	80.0	380
87	19.311	20.050	266	1276	2146	3333	458542	2832339	82.2	405
88	20.376	21.403	618	1474	2482	3648	1063549	3397183	85.4	549
•••	21.736	21.912	344	1345	2239	3092	---	---	63.3	---
89	22.019	23.853	273	1294	2183	3964	470038	4030904	115.3	1149
90	0.257	1.882	764	1369	2608	4004	1313700	4106036	111.0	1114
91	2.390	3.683	429	1204	2325	3570	737427	3228831	99.3	737
92	4.303	5.000	772	1220	2584	3263	1327353	2684294	81.4	372

(Sheet 6 of 10)

Table A1 (Continued)

Load Number	Start Time hr	End Time hr	Hopper Volume, yd^3		Displacement, tons		Bin Water Weight lb	Total Weight in Hopper lb	Average Density in Hopper lb/ft^3	In-Place Production yd^3
			Starting	Ending	Starting	Ending				
93	5.522	6.203	586	1269	2454	3276	1007249	2650906	77.3	298
94	6.753	7.787	277	1415	2207	3467	476341	2995388	78.4	358
95	8.246	9.007	989	1283	2832	3401	1699773	2838234	81.9	402
96	9.460	10.201	1063	1256	2907	3441	1828424	2896581	85.4	469
97	10.629	12.006	261	1164	2248	3551	449986	3056928	97.3	672
98	3.935	5.067	876	1215	2741	3562	1506047	3147525	95.9	673
99	5.389	6.401	487	1254	2439	3527	836974	3013426	89.0	545
100	6.839	7.706	549	1243	2499	3341	943573	2627310	78.2	311
101	8.144	8.854	245	1247	2289	3285	422316	2413755	71.7	171
102	9.432	10.415	232	967	2267	3112	399415	2090553	80.1	272
***	10.511	10.796	348	1069	2371	2994	---	---	63.8	---
103	10.837	11.851	247	1244	2290	3389	425784	2624475	78.1	308
104	12.162	13.106	501	1312	2514	3539	862282	2912222	82.2	417
105	13.572	14.321	481	1271	2491	3435	827386	2714611	79.1	336
106	14.875	15.901	494	1225	2494	3482	849380	2825157	85.4	457
107	16.260	17.215	510	1207	2516	3530	877155	2904895	89.1	528

(Sheet 7 of 10)

*** = Water Test

Table A1 (Continued)

Load Number	Start Time hr	End Time hr	Hopper Volume, yd^3 Starting	Hopper Volume, yd^3 Ending	Displacement, tons Starting	Displacement, tons Ending	Bin Water Weight lb	Total Weight in Hopper lb	Average Density in Hopper lb/ft^3	In-Place Production yd^3
108	17.564	18.601	496	1258	2504	3523	853078	2890395	85.1	463
109	19.028	20.060	253	1243	2294	3570	434862	2987705	89.0	541
110	20.447	21.315	267	1220	2307	3365	460255	2577001	78.2	305
111	21.689	22.706	247	1226	2296	3384	425898	2601971	78.5	313
112	23.062	0.601	256	1207	2296	3579	441098	3007098	92.3	594
113	0.887	1.854	507	1213	2505	3476	872177	2813209	85.9	463
114	2.374	3.260	575	1206	2561	3508	988800	2883542	88.5	515
115	3.626	4.506	603	1211	2563	3550	1036729	3010897	92.0	590
116	4.865	5.815	741	1188	2691	3430	1273776	2752691	85.8	451
117	6.271	8.011	265	1256	2302	3752	456963	3357297	99.0	762
118	8.481	9.732	267	1227	2303	3595	460239	3043327	91.8	594
119	10.146	11.231	254	1282	2284	3614	436756	3097612	89.5	568
120	11.707	13.314	587	1203	2579	3627	1009321	3104984	95.5	659
121	13.631	15.444	527	1205	2503	3625	907204	3150703	96.8	686
122	15.760	17.051	699	1357	2641	3732	1202196	3385051	92.4	669
123	17.587	19.014	649	1237	2584	3594	1115603	3136329	93.9	642

(Sheet 8 of 10)

*** = Water Test

Table A1 (Continued)

Load Number	Start Time hr	End Time hr	Hopper Volume, yd^3		Displacement, tons		Bin Water Weight lb	Total Weight In Hopper lb	Average Density in Hopper lb/ft^3	In-Place Production yd^3
			Starting	Ending	Starting	Ending				
124	19.419	20.501	261	1299	2234	3560	448726	3101824	88.4	552
125	21.064	22.424	259	1247	2219	3434	446097	2875807	85.4	465
***	22.592	22.814	325	1116	2271	3957	---	---	64.1	---
126	22.835	23.901	250	1265	2214	3378	430730	2758459	80.7	371
127	0.343	1.710	805	1215	2665	3379	1383836	2812212	85.7	460
128	2.079	3.551	547	1199	2444	3381	940119	2812951	86.8	477
129	3.894	5.251	631	1329	2490	3640	1084984	3886199	94.4	701
130	5.806	7.161	564	1422	2421	3688	970575	3504595	91.3	674
131	7.710	8.843	549	1316	2408	3414	944934	2958794	83.2	442
132	9.412	10.608	847	1222	2639	3289	1456858	2757515	83.6	418
133	11.043	12.111	1153	1142	2866	2978	1982574	2206485	71.5	154
134	12.287	14.450	251	1253	2112	3492	431812	3192341	94.3	660
135	14.883	16.925	866	1290	2590	3697	1489488	3703105	106.3	945
136	17.336	19.276	874	1267	2589	3637	1502207	3598622	105.2	903
137	19.710	21.308	1210	1236	2870	3362	2080018	3063169	91.8	597
138	21.556	23.572	313	1307	2177	3667	539487	3520123	99.7	810

(Sheet 9 of 10)

*** = Water Test

Table A1 (Concluded)

Load Number	Start Time hr	End Time hr	Hopper Volume, yd^3		Displacement, tons		Bin Water Weight lb	Total Weight in Hopper lb	Average Density in Hopper lb/ft^3	In-Place Production yd^3
			Starting	Ending	Starting	Ending				
139	0.001	2.001	656	1230	2430	3466	1127427	3198771	96.3	689
140	2.219	4.306	297	1231	2176	3420	512066	3000954	90.2	562
141	4.621	6.069	1013	1412	2777	3780	1742420	3746938	98.3	839
142	6.601	8.354	725	1314	2576	3709	1247505	3512452	99.0	797
143	8.735	10.676	746	1267	2603	3709	1282187	3494937	102.2	838
144	1.057	13.014	854	1317	2703	3739	1469150	3540197	99.5	811
145	13.408	16.519	322	1312	2260	3916	554258	3868067	109	1025
146	17.032	18.506	905	1288	2785	3785	1556414	3556059	102.	853
147	18.719	21.072	316	1350	2316	4148	544755	4208122	115.	1200
Total Calculated Bin Measure In-Place Production										84110
Average Calculated Bin Measure In-Place Production per Load										572

(Sheet 10 of 10)

Table A2
Summary of Bin Measure Load Data, Norfolk Harbor Channel Project

Load Number	Start Time hr	End Time hr	Hopper Volume, yd^3		Displacement, tons		Bin Water Weight lb	Total Weight in Hopper lb	Average Density in Hopper lb/ft^3	In-Place Production yd^3
			Starting	Ending	Starting	Ending				
1	11.222	12.414	48	2105	1849	3972	82212	4328421	76.1	1012
2	18.601	19.843	42	2104	1936	3956	72643	4112911	72.4	726
3	21.301	22.157	44	2100	1954	3980	75058	4127366	72.8	754
4	23.331	0.999	43	2108	1949	3985	74295	4146295	72.8	763
5	2.274	3.853	42	2103	1945	3978	72638	4140155	72.9	764
6	5.072	6.697	43	2106	1988	4027	73107	4151335	73.0	772
7	8.346	9.131	42	2102	1958	4016	72792	4189253	73.8	833
8	10.618	11.590	44	2095	1999	4007	74808	4091013	72.3	716
9	12.729	13.711	42	2100	1966	4010	72619	4161317	73.4	801
10	14.772	15.971	42	2098	1976	4000	72418	4120394	72.7	750
11	17.410	18.261	42	2099	1925	3968	72193	4157858	73.3	798
12	19.411	20.303	44	2106	1959	3997	75347	4152262	73.0	774
13	21.501	22.290	42	2098	1942	3988	72530	4164059	73.5	809
14	23.683	0.700	42	2108	1914	4024	72803	4292803	75.4	960
***	1.778	2.406	43	1505	1970	3224	---	---	63.5	---
15	2.672	3.251	74	2106	1929	3977	126340	4222564	74.2	869
16	4.549	5.436	42	2107	1941	3969	72774	4127857	72.6	740

(Sheet 1 of 6)

Table A2 (Continued)

Load Number	Start Time hr	End Time hr	Hopper Volume, yd^3 Starting	Hopper Volume, yd^3 Ending	Displacement, tons Starting	Displacement, tons Ending	Bin Water Weight lb	Total Weight in Hopper lb	Average Density in Hopper lb/ft^3	In-Place Production yd^3
17	6.764	7.632	45	2097	1950	3951	77088	4078904	72.0	696
18	9.058	9.528	42	2020	1941	3946	72288	4081690	74.8	877
19	12.969	13.787	42	2090	1956	4004	72435	4169619	73.9	834
20	14.974	16.012	42	2094	1965	3992	72418	4125824	73.0	766
21	17.310	18.392	42	2103	1967	4047	72447	4232081	74.5	889
22	19.925	20.574	42	2094	2008	4026	72732	4109058	72.7	743
23	21.781	22.664	42	2105	2008	4055	72803	4167145	73.3	797
24	0.011	1.090	47	2099	2061	4059	81341	4077133	71.9	690
25	2.164	3.418	94	2103	2115	4086	161074	4102725	72.2	714
26	4.750	5.479	115	2109	2155	4118	195540	4121076	72.4	726
27	7.076	7.485	42	1993	1994	3960	72952	4004627	74.4	833
***	8.440	8.897	44	760	2089	2705	---	---	63.7	---
28	9.208	9.986	43	2083	2028	4048	72999	4113000	73.1	774
29	11.265	12.301	42	2085	1983	4081	72595	4268543	75.8	977
30	13.212	14.469	62	2082	2091	4081	105330	4083498	72.6	737
31	15.747	16.761	78	2095	2020	4062	133807	4218363	74.6	888

(Sheet 2 of 6)

*** = Water Test

Table A2 (Continued)

Load Number	Start Time hr	End Time hr	Hopper Volume, yd³ Starting	Hopper Volume, yd³ Ending	Displacement, tons Starting	Displacement, tons Ending	Bin Water Weight lb	Total Weight in Hopper lb	Average Density in Hopper lb/ft³	In-Place Production yd³
32	18.054	19.076	52	2102	2059	4078	89202	4127377	72.7	750
33	19.829	20.810	73	2096	2098	4091	124525	4110739	72.6	741
34	21.733	22.921	43	2106	2047	4066	73077	4111855	72.3	720
35	0.013	0.919	69	2107	2110	4057	118276	4012514	70.5	585
36	2.011	3.269	75	2103	2130	4124	128734	4116374	72.5	733
37	4.564	5.531	122	2100	2191	4124	208659	4075120	71.9	685
38	7.042	7.686	43	2077	2012	4045	73345	4138251	73.8	821
39	8.915	10.468	43	2097	2093	4068	73023	4022042	71.0	621
40	11.807	12.175	42	2086	1979	3993	72483	4102193	72.8	762
41	13.161	14.469	43	2096	2070	4105	74193	4144101	73.2	786
42	15.876	16.617	48	2101	2018	4079	81607	4203203	74.1	855
43	17.661	18.779	42	2100	2019	4093	72684	4219369	74.4	877
44	19.843	20.876	46	2099	2019	4072	78253	4184689	73.8	833
45	22.133	23.235	46	2097	2001	4081	78097	4238169	74.8	911
46	0.478	1.531	75	2098	2085	4113	128362	4184777	73.9	837
47	2.651	3.960	62	2102	2099	4150	105262	4205479	74.1	855
48	5.018	6.165	43	2107	2051	4102	73249	4175380	73.4	802
49	7.306	8.158	42	2095	2008	4061	72922	4178770	73.8	828

(Sheet 3 of 6)

Table A2 (Continued)

Load Number	Start Time hr	End Time hr	Hopper Volume, yd^3		Displacement, tons		Bin Water Weight lb	Total Weight in Hopper lb	Average Density in Hopper lb/ft^3	In-Place Production yd^3
			Starting	Ending	Starting	Ending				
50	9.243	10.251	42	2088	2034	4070	72821	4144604	73.5	804
51	11.203	12.587	42	2093	2037	4083	72578	4165280	73.7	820
52	13.708	14.725	42	2097	2021	4050	72542	4129744	72.9	764
53	15.850	17.001	42	2100	1988	4041	72081	4177183	73.6	821
54	18.125	19.122	42	2101	1994	4019	72459	4121439	72.6	745
55	20.261	21.369	42	2101	1969	3998	72803	4132263	72.8	759
56	22.592	23.654	43	2104	1987	4061	73413	4221624	74.3	871
57	0.686	2.022	43	2103	2017	4050	73148	4138559	72.9	762
58	3.300	4.457	43	2101	2009	4074	73118	4204287	74.1	855
59	5.700	6.749	42	2104	1988	4029	72875	4156747	73.2	786
60	7.862	9.464	43	2103	2046	3998	73154	3977060	70.0	547
61	10.861	11.867	43	2097	2007	3992	73578	4042925	71.4	649
***	13.036	13.374	43	765	1997	2619	---	---	63.8	---
62	13.718	14.672	63	2105	1931	3928	106905	4100184	72.1	708
63	16.151	16.962	43	2102	1913	3938	73279	4123177	72.6	744
64	18.411	19.281	43	2103	1911	3944	73255	4140642	72.9	766
65	20.524	21.600	43	2107	1914	3963	73136	4172536	73.3	800
66	**	**	**	**	**	**	**	**	**	**

(Sheet 4 of 6)

Table A2 (Continued)

Load Number	Start Time hr	End Time hr	Hopper Volume, yd^3		Displacement, tons		Bin Water Weight lb	Total Weight in Hopper lb	Average Density in Hopper lb/ft^3	In-Place Production yd^3
			Starting	Ending	Starting	Ending				
67	**	**	**	**	**	**	**	**	**	**
68	**	**	**	**	**	**	**	**	**	**
69	**	**	**	**	**	**	**	**	**	**
70	**	**	**	**	**	**	**	**	**	**
71	16.725	17.597	42	2085	1994	3951	72881	3986756	70.8	599
72	18.883	20.492	43	2095	1975	4074	73154	4269228	75.4	956
73	22.032	23.290	43	2096	2045	4006	73452	3994759	70.6	585
74	0.665	2.246	43	2105	2056	4058	73268	4077021	71.7	676
75	3.451	4.606	43	2108	2047	4051	73577	4079939	71.7	672
76	6.037	7.172	43	2100	2060	4056	73620	4064964	71.7	670
77	8.303	9.958	43	2085	2094	3999	73238	3883673	69.0	462
78	10.706	13.062	43	2088	2063	4049	73428	4045784	71.7	672
79	14.046	15.822	42	2091	2036	4027	72483	4054468	71.8	678
80	17.300	19.510	42	2106	2045	4049	72631	4080136	71.7	678
81	20.781	22.831	64	2095	2118	4019	108658	3912031	69.1	477
82	0.018	1.133	43	2100	2076	4053	73137	4026409	71.0	620

(Sheet 5 of 6)

** = Data Not Available
*** = Water Test

Table A2 (Concluded)

Load Number	Start Time hr	End Time hr	Hopper Volume, yd^3		Displacement, tons		Bin Water Weight lb	Total Weight in Hopper lb	Average Density in Hopper lb/ft^3	In-Place Production yd^3
			Starting	Ending	Starting	Ending				
83	2.201	3.611	43	2102	2080	4011	73667	3936178	69.3	493
84	4.890	6.181	43	2103	2051	4057	73661	4084358	71.9	690
***	7.299	7.526	43	955	2099	2880	---	---	63.4	---
85	8.001	13.807	43	2050	2055	3961	73035	3885356	70.2	544
86	15.203	18.961	42	2088	2065	3993	72732	3928702	69.7	515
87	20.156	22.243	43	2095	2031	3994	73214	3999516	70.7	594
88	23.201	1.003	43	2085	2089	3967	73601	3829601	68.0	391
89	2.153	3.451	43	2064	2066	3926	73011	3793850	68.1	390
90	4.707	5.658	43	2095	2054	3804	73006	3573006	63.2	25
Average Calculated Bin Measure In-Place Production per Load										734

(Sheet 6 of 6)

*** = Water Test

Table A3
Summary of Overflow Analysis Data, Norfolk Harbor Channel Project

Load Number	Vessel Weight, Tons: Start of Overflow	Vessel Weight, Tons: End of Overflow	Solids Retained During Overflow tons	Solids Pumped During Overflow tons	Percent of Solids Retained in Hopper
1	3860	3960	100	698	14.3
2	3920	3949	29	225	12.9
3	3981	3971	-10	302	-3.3
4	3874	3986	112	803	13.9
5	3900	3982	82	785	10.4
6	3978	4026	48	522	9.2
7	3989	4007	18	237	7.6
8	3980	4001	21	567	3.7
9	3958	4012	54	346	15.6
10	3912	3995	83	610	13.6
11	3950	3963	13	191	6.8
12	3982	3979	-3	151	-2.0
13	3969	3980	11	158	7.0
14	3946	4017	71	676	10.5
15	3949	3979	30	147	20.4
16	3941	3971	30	212	14.2
17	3946	3954	8	133	6.0
18	3939	3950	3	4	75.0
19	3978	4006	28	244	11.5
20	3943	3990	47	596	7.9
21	4015	4036	21	245	8.6
22	4006	4029	23	73	31.5
23	4022	4055	33	287	11.5
24	4055	4059	4	625	0.6
25	4016	4086	70	603	11.6
26	4078	4113	35	339	10.3
27	3969	3969	0	2	0.0

(Sheet 1 of 4)

Table A3 (Continued)					
	Vessel Weight, Tons				
Load Number	Start of Overflow	End of Overflow	Solids Retained During Overflow tons	Solids Pumped During Overflow tons	Percent of Solids Retained in Hopper
28	4003	4049	46	107	43.0
29	4020	4084	64	565	11.3
30	3992	4083	91	619	14.7
31	4002	4054	52	399	13.0
32	4061	4079	18	262	6.9
33	4067	4083	16	157	10.2
34	4041	4066	25	278	9.0
35	3982	4059	77	311	24.8
36	4035	4122	87	660	13.2
37	4117	4120	3	160	1.9
38	4051	4051	0	4	0.0
39	4036	4072	36	70	51.4
40	3990	3996	6	10	60.0
41	3999	4108	107	616	17.4
42	4000	4078	78	328	23.8
43	4022	4095	73	333	21.9
44	4049	4074	25	260	9.6
45	4078	4084	6	420	1.4
46	4062	4108	46	601	7.7
47	4007	4105	143	719	19.9
48	4056	4103	47	226	20.8
49	4050	4059	9	117	7.7
50	4040	4072	32	240	13.3
51	4019	4083	64	481	13.3
52	3984	4047	63	448	14.1
53	3971	4041	70	486	14.4
54	3967	4020	53	367	14.4
55	3975	4000	25	247	10.1
56	3941	4064	123	506	24.3

(Sheet 2 of 4)

Table A3 (Continued)					
	Vessel Weight, Tons				
Load Number	Start of Overflow	End of Overflow	Solids Retained During Overflow tons	Solids Pumped During Overflow tons	Percent of Solids Retained in Hopper
57	3963	4050	87	582	14.9
58	3979	4079	100	533	18.8
59	3982	4033	51	247	20.6
60	3960	3994	34	218	15.6
61	3928	3993	65	264	24.6
62	3918	3928	10	66	15.2
63	3918	3935	17	192	8.9
64	3905	3946	41	264	15.5
65	3890	3964	74	256	28.9
66	**	**	**	**	**
67	**	**	**	**	**
68	**	**	**	**	**
69	**	**	**	**	**
70	**	**	**	**	**
71	3928	3953	25	46	54.3
72	3958	4078	120	663	18.1
73	3912	4009	97	377	25.7
74	3972	4060	88	574	15.3
75	3981	4053	72	435	16.6
76	3975	4047	72	415	17.3
77	3819	4003	184	208	88.5
78	3979	4055	76	416	18.3
79	3964	4032	68	292	23.3
80	3999	4039	40	690	5.8
81	3975	4022	47	333	14.1
82	3933	4055	122	287	42.5
83	3923	4006	83	232	35.8

(Sheet 3 of 4)

** = Data Not Available

Table A3 (Concluded)

Load Number	Vessel Weight, Tons: Start of Overflow	Vessel Weight, Tons: End of Overflow	Solids Retained During Overflow tons	Solids Pumped During Overflow tons	Percent of Solids Retained in Hopper
84	3970	4077	107	201	53.2
85	3903	3948	45	237	19.0
86	3880	3993	113	407	27.8
87	3896	3995	99	254	39.0
88	3940	3963	23	69	33.3
89	3892	3900	8	8	100.0
90	3796	3801	5	11	45.5
Project Totals			4419	28555	
Project Averages			52	336	15.5

(Sheet 4 of 4)

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13. ABSTRACT *(Maximum 200 words)*

The installation, testing, and analysis of data from an automated monitoring system aboard a contract hopper dredge is detailed in this report. The automated dredge monitoring system consists of sensors to monitor the dredge displacement, volume of material in the hopper, velocity and density of material in the drag arms, drag arm depth, and vessel position, as well as a data acquisition system to store and manage the information. The data are recorded continuously during two dredging projects performed for the U.S. Army Corps of Engineers. Detailed analysis of the data is performed to determine the bin measure production and overflow efficiency during the two projects. A detailed uncertainty analysis is also performed.

14. SUBJECT TERMS

Acoustic sensors	Dredge	Dredge production	Uncertainty
Automated monitoring	Dredge data	Hopper dredge	
Bin measure	Dredge monitoring	Overflow	

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